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All About Space Annual

Interstellar travel

Exploring beyond deep space

Stunning discoveries and findings

The secrets of space exploration

Story of the Moon landing

Robots in space

Mysteries of the universe

The latest space tech

Digital Edition

FUTURE
VOLUME 7

Everything you want to know about our galaxy and beyond

Welcome to the All About Space Annual

2019 has been an incredible year in the world of space and astronomy, with Virgin Galactic taking its first test passenger to space, the capture of the first-ever image of a black hole, July marking the 50th anniversary of the historic moment that humankind set foot on the Moon for the first time, and much more. In the **All About Space Annual 2020** we look back at some of the highlights of the past year and bring you the best of **All About Space** from the past 12 months.

Uncover the secrets of the Apollo 11 mission as Buzz Aldrin and the last crew members reveal the unpublished archives of the 1969 Moon landing, and learn about the mysterious Galaxy X and whether astronomers are any closer to locating it. Meet SpaceX's Starship Hopper, which could take humans to Mars in the not-too-distant future, and China's latest space station, as we examine the latest space tech. Explore the origins of the ice giant Uranus, and find out why our Sun is getting hotter and what its future holds. Think you understand gravity? Think again, as we discover why some physicists are looking to replace the theory surrounding the everyday force. Enjoy!

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All About Space Annual

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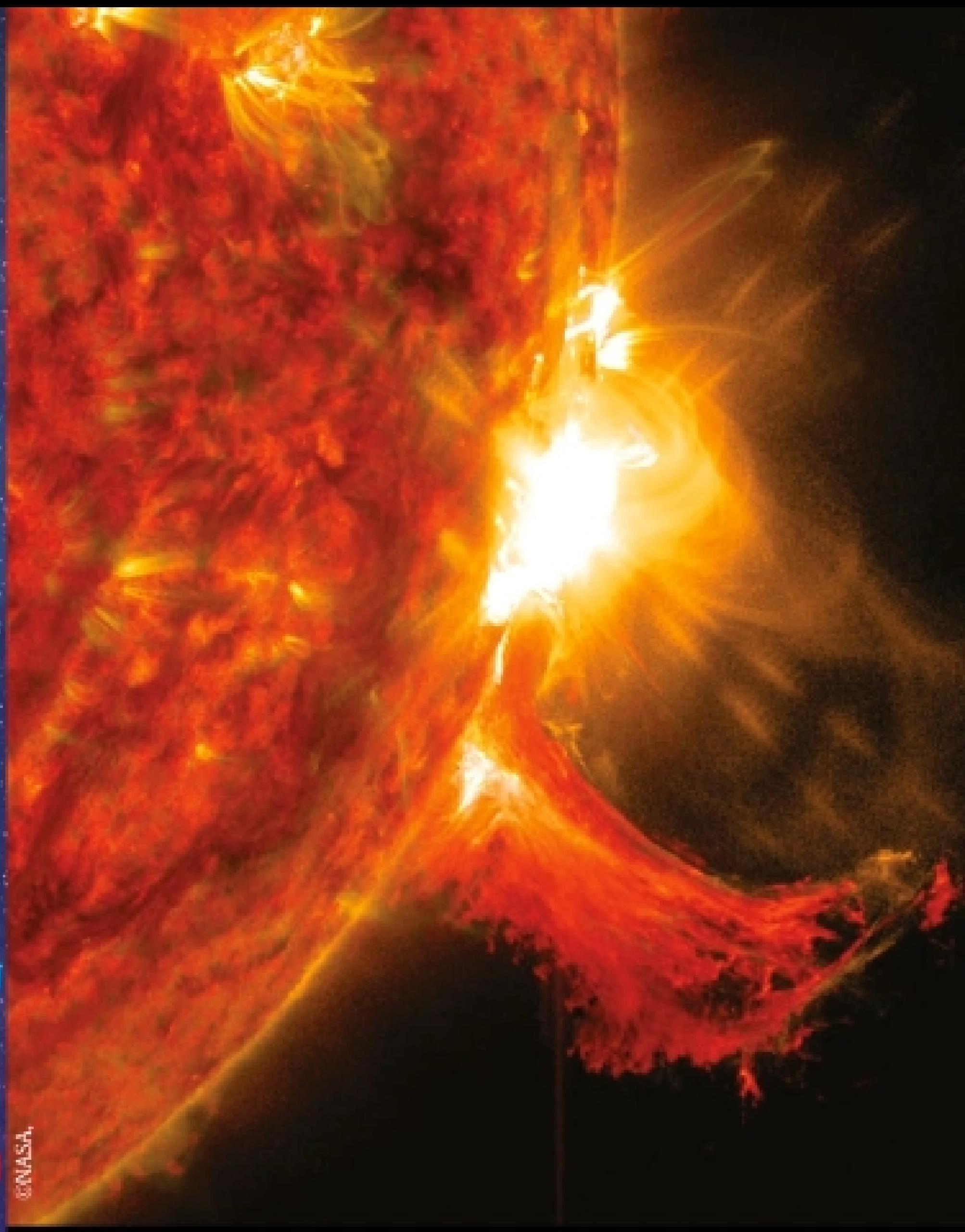
> "2019 has been a fantastic year in astronomy, space science and space exploration"



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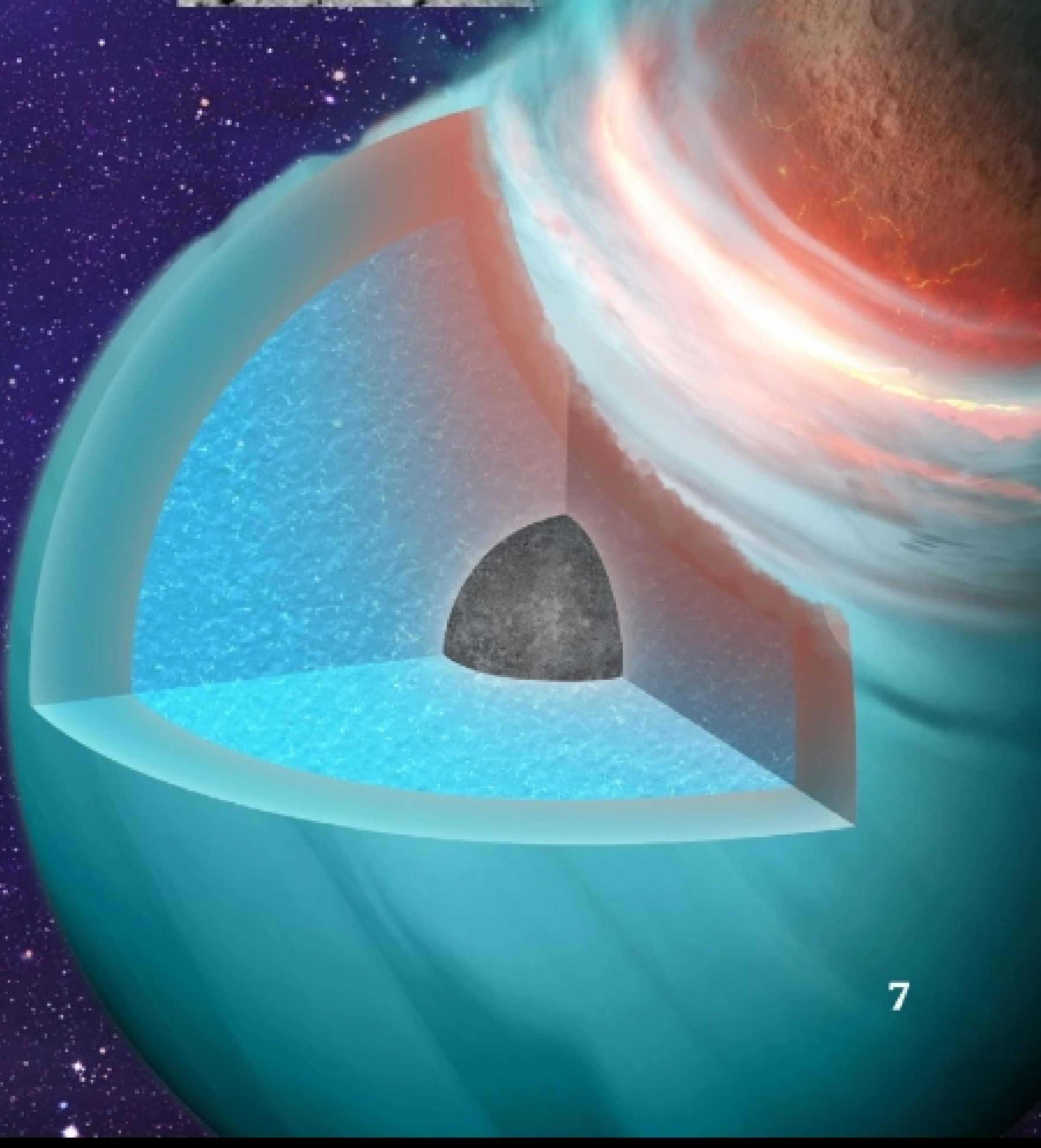
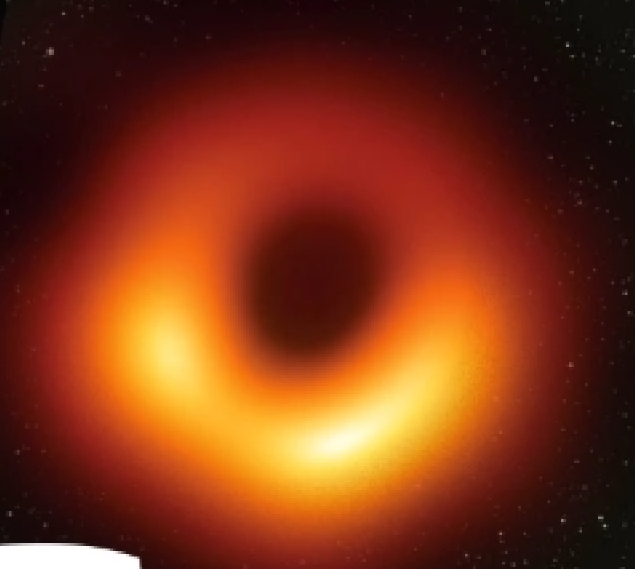




A LOOK BACK OVER

2019'S GREATEST HITS

Every month, there has been an event worthy of celebration, and to fit them into six pages does not do the year justice

2019 has been a year of highs and lows, but the highs take the majority vote. It has been a fantastic year in astronomy, space science and space exploration, where we've reaped the rewards of some landmark missions as well as basked in rare astronomical phenomena. Examples of this include NASA's New Horizons flyby of Ultima Thule and South America's total solar eclipse. However, one stand-out event caught the attention of people worldwide as everyone cast their mind back 50 years to the historic Apollo 11 Moon landing. This feat truly explored the next frontier and entered humanity into the space age.

It is this inception of the space era that has led to these incredible achievements, notable anniversaries and awe-inspiring discoveries. They are all thanks to humanity's progression in technology and ambition. Space agencies all over the world are exploring the farthest and most alien regions of the Solar System while space- and ground-based telescopes have revealed mysteries about the universe that would have once seemed impossible. Even planets the size of Earth – Earth 2.0s if you will – have been found in planetary systems light years away.

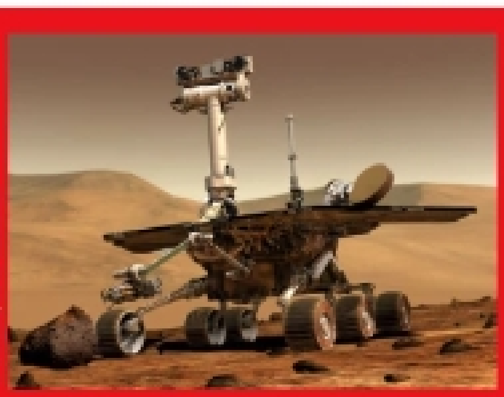
Private space companies have made a real surge in 2019 as well, with companies such as SpaceX, Boeing and Virgin Galactic – to name just a few – becoming a regular presence in space and they are now cooperating with government space agencies to focus their efforts on a lunar outpost. Sadly, some endeavours have met their end, but there are others that are only just beginning, and the enormous potential for 2020 is an extremely tantalising prospect.

Ambitious Beresheet mission launches

Date: 21 February

The Israeli non-profit organisation SpaceIL launched the Beresheet lunar lander, with hopes of it becoming the first privately funded, and Israeli, Moon landing. Sadly, it crash-landed on the lunar surface in April.

© SpaceIL



© NASA/JPL-Caltech

Anniversary of Spirit and Opportunity's arrival

Date: 3 & 25 January

15 years ago, NASA's twin Mars Exploration Rovers touched down. Spirit and Opportunity both had fruitful endeavours, operating for over six and 14 years respectively.

Conjunction of Venus and Jupiter

Date: 22 January

Just after the Blood Moon, two of the brightest objects in the night sky, the planets Venus and Jupiter, were seen just 2.4 degrees apart.

Virgin Galactic flies its first test passenger

Date: 22 February

Its SpaceShipTwo VSS Unity reached space for the second time, with Dave Mackay, Michael Masucci and its first test passenger, Beth Moses.

© Virgin Galactic 2018

JANUARY

FEBRUARY

The Moon bleeds in the sky

Date: 20 January

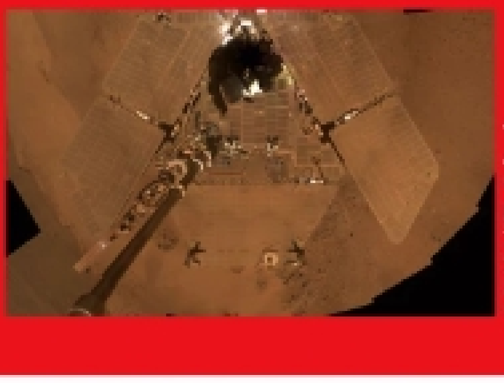
When the Moon passed through the Earth's shadow (known as the umbra), it turned darker before becoming stained red and everyone was treated to a rare sighting of a 'Blood Moon'.

© ESA

NASA call it a day for Opportunity

Date: 13 February

NASA declared that it was ending its attempts to contact the Opportunity rover, which had fallen victim to a global dust-storm in June 2018, concluding the longest-serving rover on another planet.



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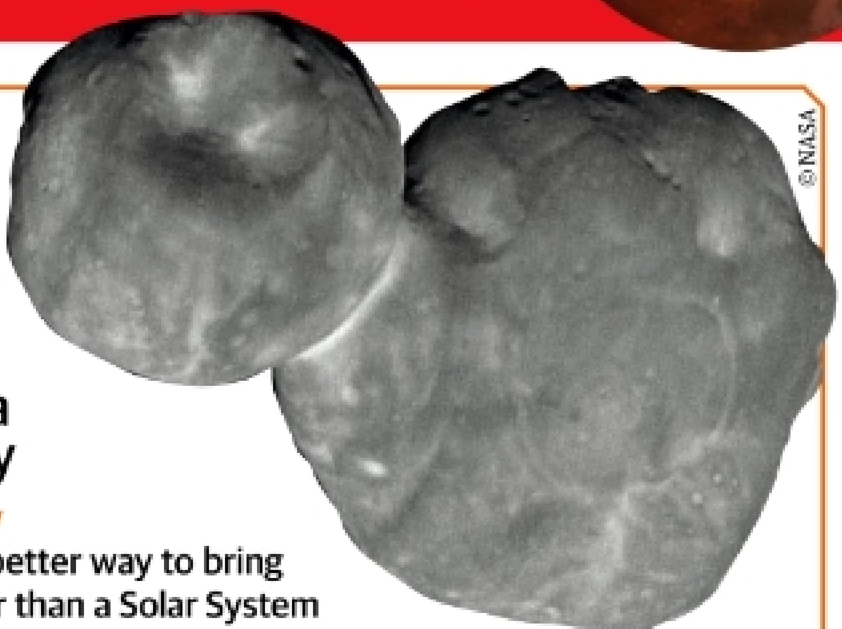


© NASA

The Ultima Thule flyby

Date: 1 January

There was no better way to bring in the new year than a Solar System flyby that will go down in the history books. From the same spacecraft that brought us the Pluto flyby of 2015, NASA's New Horizons sent back images from the first-ever flyby of a Kuiper Belt Object. This object sits beyond the orbit of Neptune, and (486958) 2014 MU69 – later renamed Ultima Thule – revealed itself to be a rocky, cratered object with an interesting bi-lobial (consisting of two lobes) appearance.

What makes Ultima Thule a target of interest is the fact that scientists now have up-close data about a time-capsule, frozen in space from the Solar System's birth. This object is a rarity to come across, and being situated beyond the orbit of Neptune, about 6.6 billion kilometres (4.1 billion miles) away from Earth, no one is entirely sure when an opportunity like this will ever happen again.

Astronomers explore the lunar far-side for a Chang'e

The China National Space Administration (CNSA) launched a landmark mission that saw the first ever lander and rover successfully deployed onto the far-side of the Moon. The Chang'e 4 lander and its rover, Yutu-2, arrived at the Von Kármán crater in the South Pole-Aitken Basin on the 3 January 2019. They are both still operating at the time of writing.

In a year of some unfortunate lunar crash landings, this dynamic duo has exceeded exceptions as they inspect the previously unexplored terrain. Such a feat was not possible without the help of their relay satellite, Queqiao, which relays communications between Earth and the far-side.

© CLEP/Planetary Society

© NASA

The first Apollo anniversary of 2019

Date: 13 March

In a year full of notable Apollo anniversaries, Apollo 9 was the first. 50 years prior, James McDivitt, David Scott and Russell Schweickart performed the first rendezvous of the lunar and command services modules in space.

© SpaceX

SpaceX passes Demo-1 with flying colours

Date: 8 March

Demo-1 was SpaceX's first test flight of its Dragon 2 capsule. Built to aid NASA's Commercial Crew program, the uncrewed capsule made its way to the ISS and back in just six days.

TESS is off the exoplanetary mark

Date: 16 April

NASA's Transiting Exoplanet Survey Satellite (TESS) team is reported to have found its first Earth-sized exoplanet, HD 21749c.

© NASA

Uncertainty over universal expansion

Date: 25 April

Astronomers announced discrepancies in the rate of universal expansion measured, known as the 'Hubble Constant'.

© NASA/ESA

MARCH

APRIL

Space telescopes 'weigh' the Milky Way

Date: 7 March

ESA's Gaia satellite and NASA/ESA's Hubble Space Telescope provided a more accurate measurement of our galaxy's mass, finding it's 1.5 trillion times that of our Sun.

© NASA/ESA

InSight hears a marsquake

Date: 6 April

NASA's Interior Exploration using Seismic Investigations, Geodesy and Heat Transport (InSight) lander heard a distinctive tremor that turned out to be a marsquake. This was its first detection since landing in November 2018.

© NASA/JPL-Caltech

Curiosity hits the jackpot

NASA's Curiosity rover has been on Mars since 6 April 2012 and it finally sampled its first "clay-bearing unit" on 6 April 2019 – or what some people may want to call the 2,370th 'sol,' which is a Martian day that is roughly 40 minutes longer than an Earth day.

Scientists and engineers have been excited to explore such a region since before the rover was launched; this is because clay minerals are usually formed in water. So by having a clay-bearing sample, they can understand a bit more about ancient water of the Red Planet. The sample was found whilst drilling into a bedrock nicknamed 'Aberlady' whilst exploring the slopes of Mount Sharp.

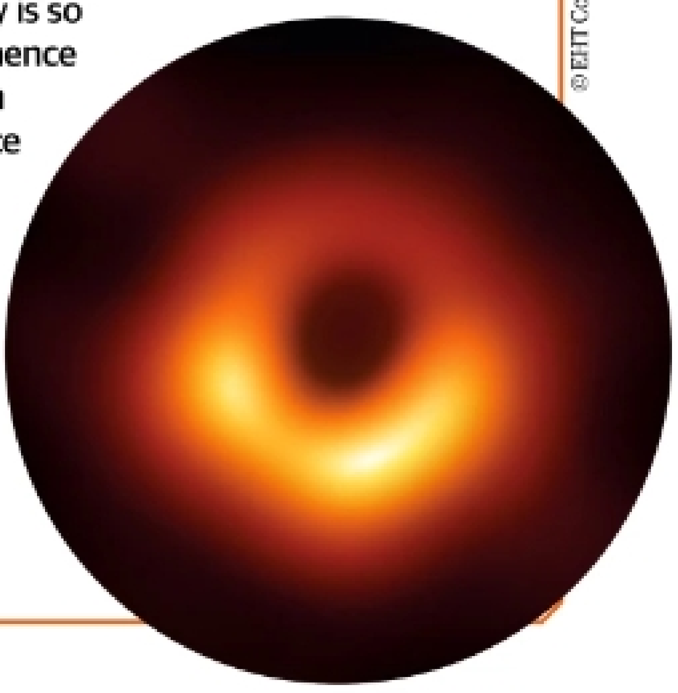
© NASA/JPL-Caltech

Behold! The first-ever image of a black hole

Date: 10 April

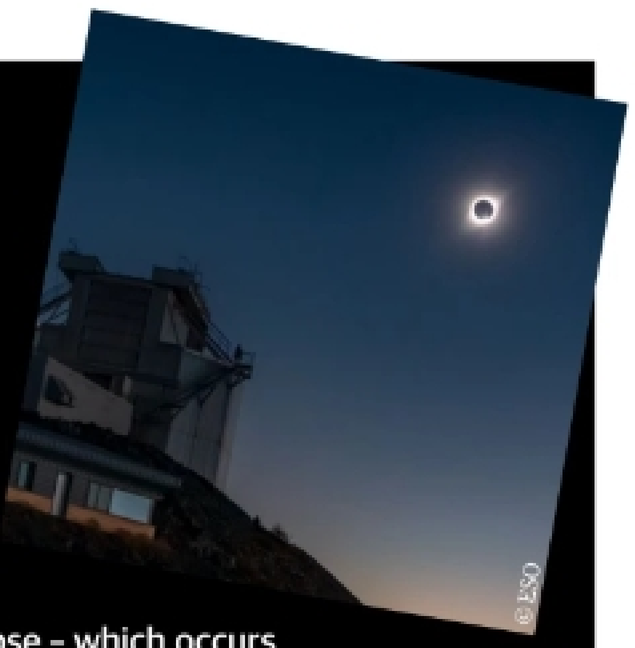
A truly magnificent collaborative achievement in 2019 was imaging a region of space that has forever been in the imagination of science and science-fiction fans alike: the black hole. Using a global team of telescopes, the Event Horizons Telescope (EHT) team were able to image the region around the black hole at the centre of a galaxy called Messier 87.

To put this achievement into perspective, it was equivalent to seeing an orange on the Moon! This black hole has the same mass as 6.5 billion Suns, and its gravity is so great that no light can escape – hence the name. But this silhouette can still reveal a lot about its influence on the surrounding gas, which is moving at incredible speeds and emitting lots of radiation. The telescopes from around the world, including the United States, Spain, Mexico, Antarctica and others, show what can happen when the world collaborates.



© EHT Collaboration

The 2019 total solar eclipse


© ESO

2 July 2019 saw a total solar eclipse stretch over the South Pacific Ocean and parts of South America. The main beneficiaries of this eclipse – which occurs when the Moon and the Sun align to block out the sunlight – were the residents of Chile and a small section of Argentina.

The European Southern Observatory's La Silla Observatory opened its doors to the public, astronomers and even the president of Chile to experience totality (the term used to describe the Moon's full silhouette). The sky was dark enough during totality to also observe Venus, Mars and the brighter stars.

The 50th anniversary of Apollo 11

Date: 20 July

The moment that inspired generations was celebrated around the world as people reminisced about what happened 50 years prior and remembered where they were when it happened. NASA's Apollo 11 Moon landing was not only an event that pushed the Americans ahead of the Soviets in the Space Race, but it was the pinnacle of years of hard work from thousands of people.

July 2019 was exciting as people celebrated and commemorated when Neil Armstrong and Edwin 'Buzz' Aldrin stepped off the Lunar Module Eagle onto the Sea of Tranquility and set the first footprints on the Moon – all whilst Michael Collins was onboard the Command Module Columbia in lunar orbit. Not only was this a celebration of a historic event, but an opportunity to reflect on space exploration over the last 50 years.

© NASA

©NASA

Astronomers purr over Ultima Thule's first results

Date: 16 May

NASA's New Horizons team published the initial results from the historic flyby, consisting of its development, geology and composition.

Hawaiians protest telescope construction

Date: 15 July

Protests escalated in Hawaii with 33 arrested. Hundreds of natives were protesting the Thirty Meter Telescope's construction.

20th anniversary of Eileen Collins' milestone

Date: 23 July

The NASA astronaut became the first female commander of a Space Shuttle mission in 1999, launching the Chandra X-ray Observatory.

© NASA

MAY

JUNE

JULY

New Shepard reaches new heights

Date: 2 May

Blue Origin reached a personal-best altitude of 106 kilometres (66 miles) whilst testing its reusable rocket-capsule duo and carrying 38 science experiments.

©Blue Origin

Ryugu welcomes the Hayabusa-2 probe

Date: 27 June

The JAXA mission arrived at the near-Earth asteroid 162173 Ryugu a year ago, performing remote sensing duties and undergoing a successful sample collection.

© JAXA

© Adrian Mann

Comet Interceptor gets the green light

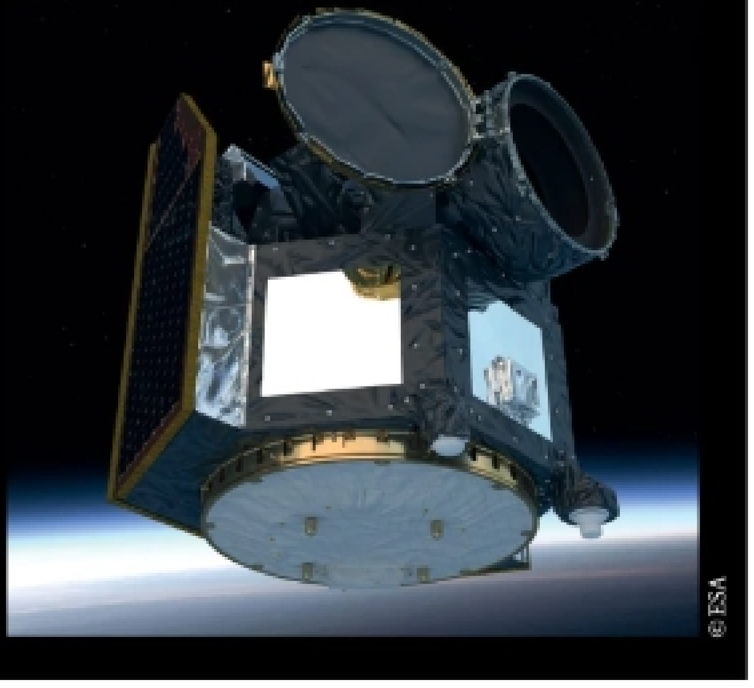
Date: 19 June

ESA announced its next addition to its Cosmic Vision program: the Comet Interceptor mission. This three-spacecraft mission will visit a pristine comet, or recently introduced Solar System object, for a close-up inspection.

CHEOPS furthers exoplanet understanding

The final hurdle of 2019 could see the launch of the ESA and Swiss Space Office's exoplanet-characterising extraordinaire. The Characterising Exoplanets Satellite, abbreviated to CHEOPS and named after the pharaoh of the Great Pyramid of Giza, could soon be launched into a Sun-synchronous orbit to stare at known exoplanets in the cosmos and perform ultra-high photometry on bright stars.

The satellite will measure the bulk density of super-Earths and Neptune-sized exoplanets.


© ESA

India's important lesson in lunar landing

Date: 2 September

Despite recent success, 2019 saw the best and the worst of space exploration for India. The Indian Space Research Organisation (ISRO) was giddy with excitement as its Chandrayaan-2 spacecraft entered lunar orbit on 20 August 2019. But when the day came to separate its Vikram lander on 2 September, so it could investigate lunar water ice on the south pole region, ISRO lost contact with Vikram seconds before touchdown and it supposedly crashed.

© Getty

© OGLE

The Milky Way is viewed in 3D

Date: 1 August

Astronomers accumulated data on over 2,400 Cepheid stars to reveal our galaxy's unusual shape. It appears to be warped, with one side bent 'up' and the other 'down'.

First Emirati astronaut emerges

Date: 25 September

Hazzaa Ali Almansoori became the first astronaut from the United Arab Emirates when he spent eight days on the ISS.

Happy birthday to NASA

Date: 1 October

NASA had 61 candles on his birthday cake. Its genesis was in response to the Soviets' launch of Sputnik.

© NASA

AUGUST

SEPTEMBER

OCTOBER

TESS spots an alluring exoplanet

Date: 31 July

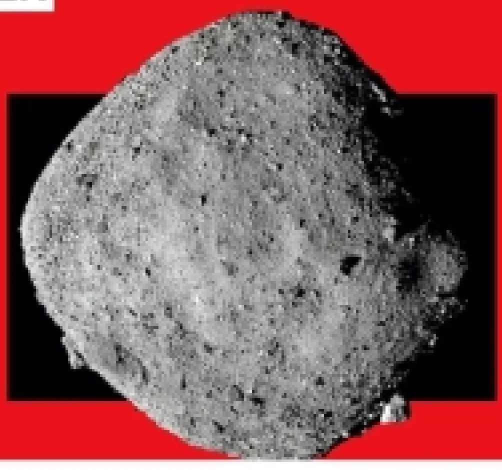
Another exciting discovery from TESS was the unearthing of the exoplanet GJ 357-d, a super-Earth just 31 light years away. It resides in the star's habitable zone, where water could potentially exist as a liquid.

© NASA

OSIRIS-REx eyes up its target

Date: 12 August

NASA narrowed down its sample collection site to just four locations on the asteroid Bennu. The OSIRIS-REx spacecraft will take a sample from just one, but all four are geologically diverse and deemed reachable.


© NASA

© Tobias Roetsch

Interstellar intruder found by amateur astronomer

Date: 25 September

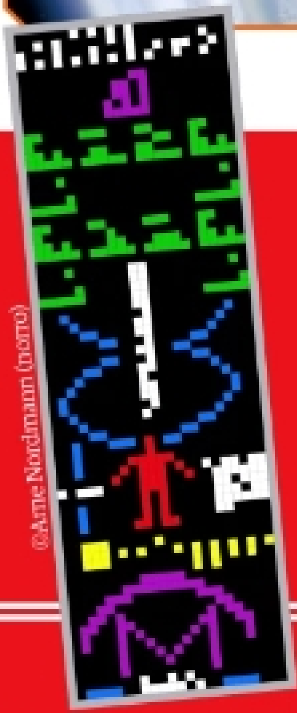
The International Astronomical Union officially stated that the recently discovered Comet C/2019 Q4 (Borisov) is not from our own Solar System. This is the second interstellar visitor discovered in two years, after 'Oumuamua.

© Adrian Mann

Boeing tests the Starliner

Date: 17 December

After a long year for the Commercial Crew program, Boeing will finally perform an uncrewed test of its CST-100 Starliner vessel, sending it to the ISS and back.



©Arne Nordmann (norro)

The Arecibo anniversary

Date: 16 November

45 years ago, humans sent our first message to extraterrestrial life, directed at the M13 star cluster. It was projected from the Arecibo radio telescope in Puerto Rico, hence why it's known as the 'Arecibo message'.

Annular Solar Eclipse

Date: 26 December

This eclipse occurs when the Moon is at its farthest point from Earth – due to its elliptical orbit – in front of the Sun and produces a magnificent sight: the 'ring of fire'.

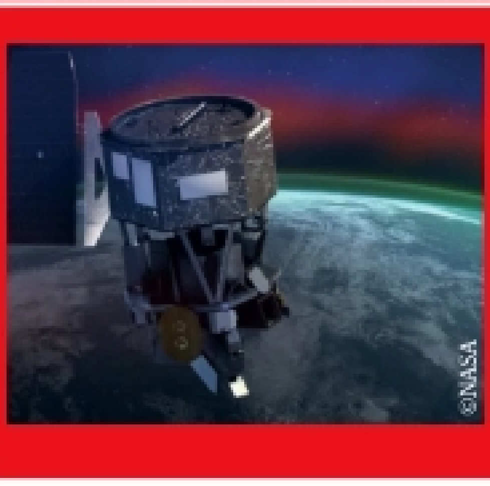
NOVEMBER

DECEMBER

NASA's ICON mission finally launched

Date: 11 October

NASA eventually launched its long-delayed mission designed to carefully study the Earth's ionosphere – the region of the atmosphere ionised by solar radiation.



©NASA

Apollo 12: Return to the Moon

Date: 19 November

Apollo 11's successor also had an adventure to the Moon, as NASA sent Charles 'Pete' Conrad, Alan Bean and Richard Gordon to space. Conrad and Bean became the third and fourth humans to step onto the Moon.

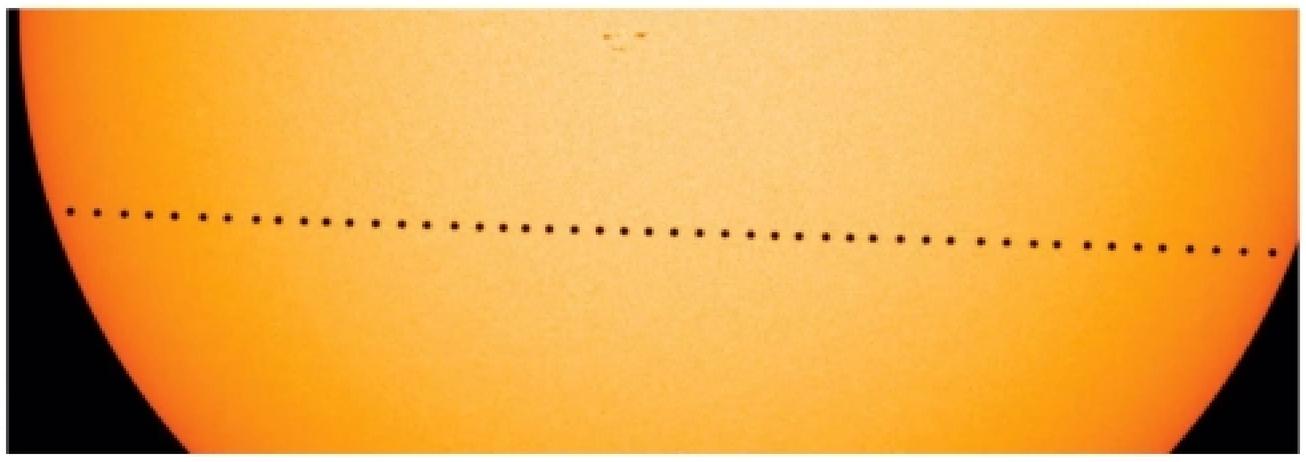
©NASA

Mercury's transit of the Sun

Date: 11 November

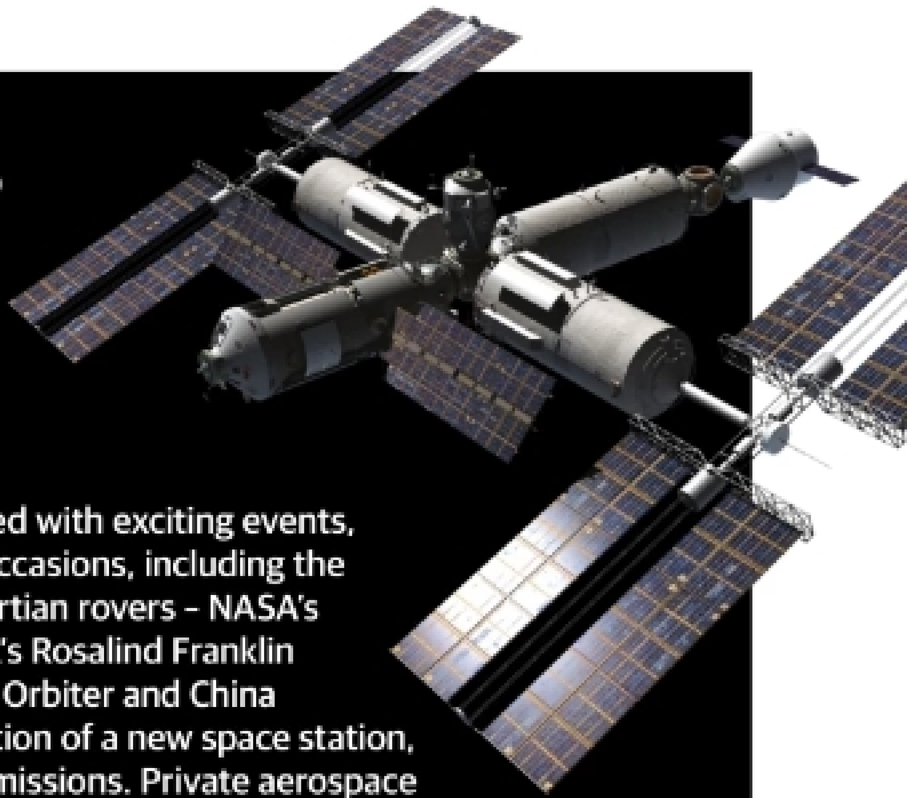
An astronomical event that has not happened since 2016 and one that astronomers love to capture on camera, mostly for its simplicity, is the transit of Mercury in front of the Sun. This is an event that occurs roughly 13 times per century, and the next one won't occur until 2032. The transit is a rare event when a celestial object moves in front of our view of the Sun. This can happen with Mercury and Venus, as they are inside the orbit of the Sun and Earth.

For the 2019 transit of Mercury, its silhouette passed in front of the Sun for about five and a half hours and crossing from east to west. The entire transit was best viewed in the continent of South America, as well as western Africa, the east coast of the United States, Mexico and islands in the south of North America.



© NASA

What's ahead for 2020



2020 will be mobbed with exciting events, anniversaries and occasions, including the launches of two Martian rovers – NASA's Mars 2020 and ESA's Rosalind Franklin rovers – ESA's Solar Orbiter and China beginning construction of a new space station, to name just a few missions. Private aerospace companies will continue their surge into space with the first crewed test mission of NASA's Commercial Crew program, launching astronauts onboard SpaceX's Crew Dragon and Boeing's CST-100 Starliner.

The wonderful nature of the cosmos will bring more celestial masterpieces, including another total solar eclipse visiting Chile and Argentina and an extremely rare conjunction between Jupiter and Saturn, both in the month of December 2020.

© Adrian Mann

Exploration

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THE SECRETS OF APOLLO 1

Buzz Aldrin & the last crew

unpublished archives of the

members reveal the 1969 Moon landing

Fifty years ago, humankind achieved one of the greatest technical feats of all time. Less than nine years after President Kennedy had set the goal of landing a man on the surface of the Moon and returning him safely to Earth, NASA achieved that most astonishing aim on 20 July 1969.

Those intervening years had been a white-knuckle ride. Beginning with Alan Shepard's 15-minute suborbital Mercury flight in 1961, NASA progressed through a series of milestones in their mission to reach the Moon. There was the loss of a Mercury capsule and the near-drowning of its pilot Gus Grissom; John Glenn's re-entry with a retrorocket still attached to his Friendship 7 capsule; a slew of hugely successful Gemini missions, including one that almost span out of control, potentially threatening the life of the astronaut who in 1969 would take that first historic step and then four fully flown Apollo missions: two in low-Earth orbit, two that orbited the Moon and only one to test the full system. NASA had to endure the catastrophic loss of Grissom and his two crew mates, Edward White and Roger Chaffee, in 1967 in Apollo 1's tragic fire on the launch pad, but the space agency had resolved to carry on, completely redesigning the Lunar Command Module and carrying out major changes to the Lunar Landing Module - the LEM as it was known - in that short space of time.

> "A space mission will never be routine. You're putting three humans on top of an enormous amount of high explosive" Gene Kranz

Amid triumph and tragedy, on 16 July 1969 NASA was ready to go to the Moon. Yet the trials and tribulations of the previous years were not over, and the three-man crew of Apollo 11 - Neil Armstrong, Buzz Aldrin and Michael Collins - were facing one of the most dramatic spaceflights in history. We recall the historic first words said on the lunar surface and the elation of the largest TV audience in history at that time when they saw those grainy black-and-white images from the Moon, but there is so much more to the story of Apollo 11 that may not be as well known.

Their first task, of course, was to leave Earth on top of the mighty Saturn V rocket - the tallest, most powerful rocket ever built. Many astronauts who were propelled into space by the Saturn V describe it as being a very smooth ride. Neil Armstrong is quoted as saying that while the launch for all those watching on Cocoa Beach or at Cape Canaveral was deafening, the crew could only detect a slight increase in background noise,

© NASA/Getty

No escape plan: what NASA didn't want the astronauts to know

A secret launch document revealed that an escape plan – should the Saturn V rocket fail – was bogus

What the astronauts were told

The crew were told that should the leak cause an engine to fail at liftoff, their capsule would eject to safety far away from the failing, exploding rocket. To their knowledge, Armstrong and his crew had been sufficiently trained to escape.

What would have happened

Apollo 11 would not be saved if something had gone wrong in the first two minutes after liftoff. The abort system needed two seconds after detection of a catastrophic failure to activate the launch escape system. If an engine were to go out on the first stage, within half a second the Saturn V would have broken up and killed the crew.

a lot of shaking and feeling akin to being on board a large jet aeroplane on takeoff. Yet as smooth a ride as it was, being on top of that much rocket fuel was always a dangerous experience. "A space mission will never be routine because you're putting three humans on top of an enormous amount of high explosive," Gene Kranz, flight director for Apollo 11's lunar landing, told us. If there were any nerves, the astronauts weren't feeling it, according to Buzz Aldrin. "We felt that our survival was in the probability of 99 per cent. There were a lot of risks involved but there were a lot of points to abort the mission short of continuing on something risky."

Once in space the Command Service Module had to rotate and dock with the Lunar Module, which was embedded in the final S-IVB stage of the Saturn V rocket. After the two spacecraft had mated, onwards they flew to the Moon, leaving the S-IVB stage trailing in space behind them. Some time later, the crew spotted something strange outside: a light that appeared to be following them. When Michael Collins used the onboard telescope to view it, he couldn't make it out – it looked like a series of ellipses, and when focusing the telescope it seemed L-shaped, but that could have just been the way sunlight was glinting off it.

Reticent to tell mission control in Houston, Texas, that they were being raced to the Moon by a UFO, the crew cautiously asked where the SIVB rocket stage was. "A few moments later they came back to us and said it was around 6,000 miles [9,656 kilometres] away," recalled Aldrin. "We really didn't think we were looking at something that far away, so we decided to go to sleep and not talk about it anymore." Aldrin doesn't believe it was an alien spaceship, but that it was more likely the Sun reflecting off one of four metal panels that fell away from the rocket stage when they docked with the Lunar Module. For almost four days Apollo 11 flew towards the Moon, where Armstrong and Aldrin climbed into the Lunar Module – the 'Eagle' – and said goodbye to Collins, who was to remain in the Command Module in orbit around the Moon.

As the Eagle flew around the far side of the Moon, things in mission control were growing tense. "There was a degree of seriousness in mission control that I hadn't even seen in training," said Kranz. "That was when you realised this was the real deal: today, we land on the Moon." Almost immediately after separating from the Command Module there were problems. Radio communication with the Eagle was sketchy at best, and they were coming up to the point where the landing could no longer be aborted if something was wrong.

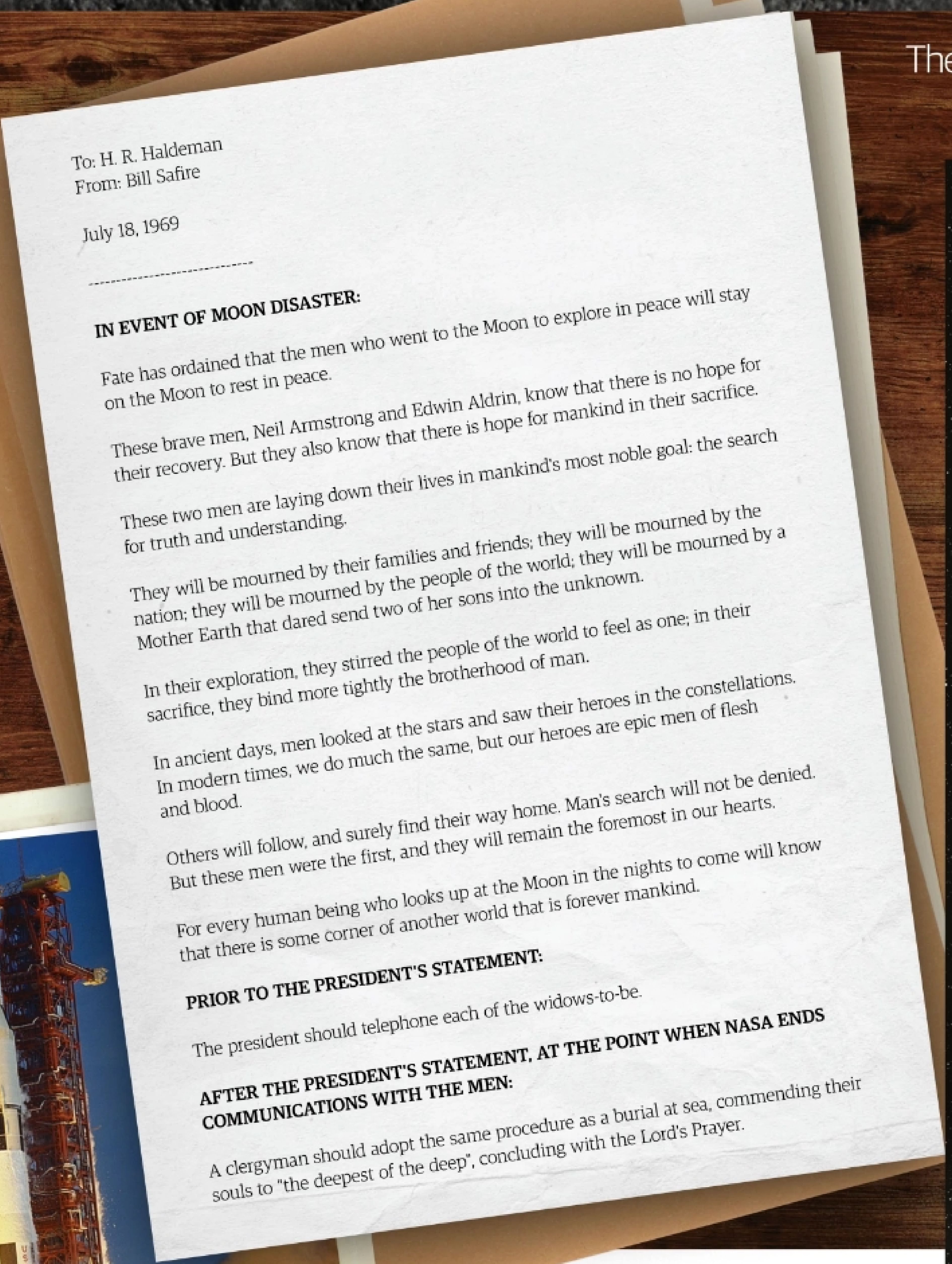
"It was up to me to decide if we had enough information to make the go/no-go [decision] and continue the descent to the Moon," said Kranz. So, five minutes before the powered descent to the lunar surface was due to begin, with radio communication cutting in and out, Kranz asked

> "There was a degree of seriousness in mission control that I hadn't even seen in training"
>
> Gene Kranz

Left: The Apollo 11 crew 'suit up' for a countdown demonstration test

Right top: The huge Saturn V rocket carries three men towards the Moon

Right bottom: In his spacesuit, Neil Armstrong practises getting back to the first rung of the ladder on the Lunar Module



To: H. R. Haldeman
From: Bill Safire

July 18, 1969

IN EVENT OF MOON DISASTER:

Fate has ordained that the men who went to the Moon to explore in peace will stay on the Moon to rest in peace.

These brave men, Neil Armstrong and Edwin Aldrin, know that there is no hope for their recovery. But they also know that there is hope for mankind in their sacrifice.

These two men are laying down their lives in mankind's most noble goal: the search for truth and understanding.

They will be mourned by their families and friends; they will be mourned by the nation; they will be mourned by the people of the world; they will be mourned by a Mother Earth that dared send two of her sons into the unknown.

In their exploration, they stirred the people of the world to feel as one; in their sacrifice, they bind more tightly the brotherhood of man.

In ancient days, men looked at the stars and saw their heroes in the constellations. In modern times, we do much the same, but our heroes are epic men of flesh and blood.

Others will follow, and surely find their way home. Man's search will not be denied. But these men were the first, and they will remain the foremost in our hearts.

For every human being who looks up at the Moon in the nights to come will know that there is some corner of another world that is forever mankind.

PRIOR TO THE PRESIDENT'S STATEMENT:

The president should telephone each of the widows-to-be.

AFTER THE PRESIDENT'S STATEMENT, AT THE POINT WHEN NASA ENDS COMMUNICATIONS WITH THE MEN:

A clergyman should adopt the same procedure as a burial at sea, commending their souls to "the deepest of the deep", concluding with the Lord's Prayer.

his flight controllers to give him their go/no-go based on the last frame of data that they saw. They all said "go." And then things turned from bad to nearly catastrophic. The spacecraft's guidance computer, developed at MIT under the auspices of Charles Draper - the lab at MIT now bears his name - was a 2MHz system that was the first in the world to use integrated circuits. Its fixed memory was an ingeniously designed 'Core Rope' which consisted of a set of small hoops. 'Little Old Ladies', as it was referred to at the time, along with machines would thread the code either through or around the hoops to give the computer its 1 or 0 value. If the MIT code was threaded incorrectly, the 'programmer' would have to laboriously go through the woven cores and debug it. When the crew were approaching the Moon for the landing, various alarms were triggered by the computer. "Whatever information we were looking at [disappeared] and instead it gave us the code number of the alarm," said Aldrin. "It was

Mission control loses contact with Apollo 11

Alarms, loss of communication and system failures plagued the first mission to land on the Moon

03:04:15:47
"Apollo 11, Apollo 11, this is Houston. Do you read? Over."
Bruce McCandless, CAPCOM

03:04:15:59
"Apollo 11, Apollo 11, this is Houston. Do you read? Over."
Bruce McCandless, CAPCOM

03:04:17:00
"Apollo 11, Apollo 11, this is Houston. We are reading you weakly. Go ahead. Over."
Bruce McCandless, CAPCOM

03:04:19:32
"Apollo 11, this is Houston. Are you in the process of acquiring data on the burn? Over."
Bruce McCandless, CAPCOM

03:04:21:37
"Apollo 11, Apollo 11, this is Houston. How do you read?"
Bruce McCandless, CAPCOM

03:04:16:11
"…"
Unidentified crew member, Apollo 11

03:04:16:59
"Houston, Apollo 11. Over."
Unidentified crew member, Apollo 11

03:04:21:43
"Reading you loud and clear, Houston. How's us?"
Neil Armstrong, Apollo 11 commander

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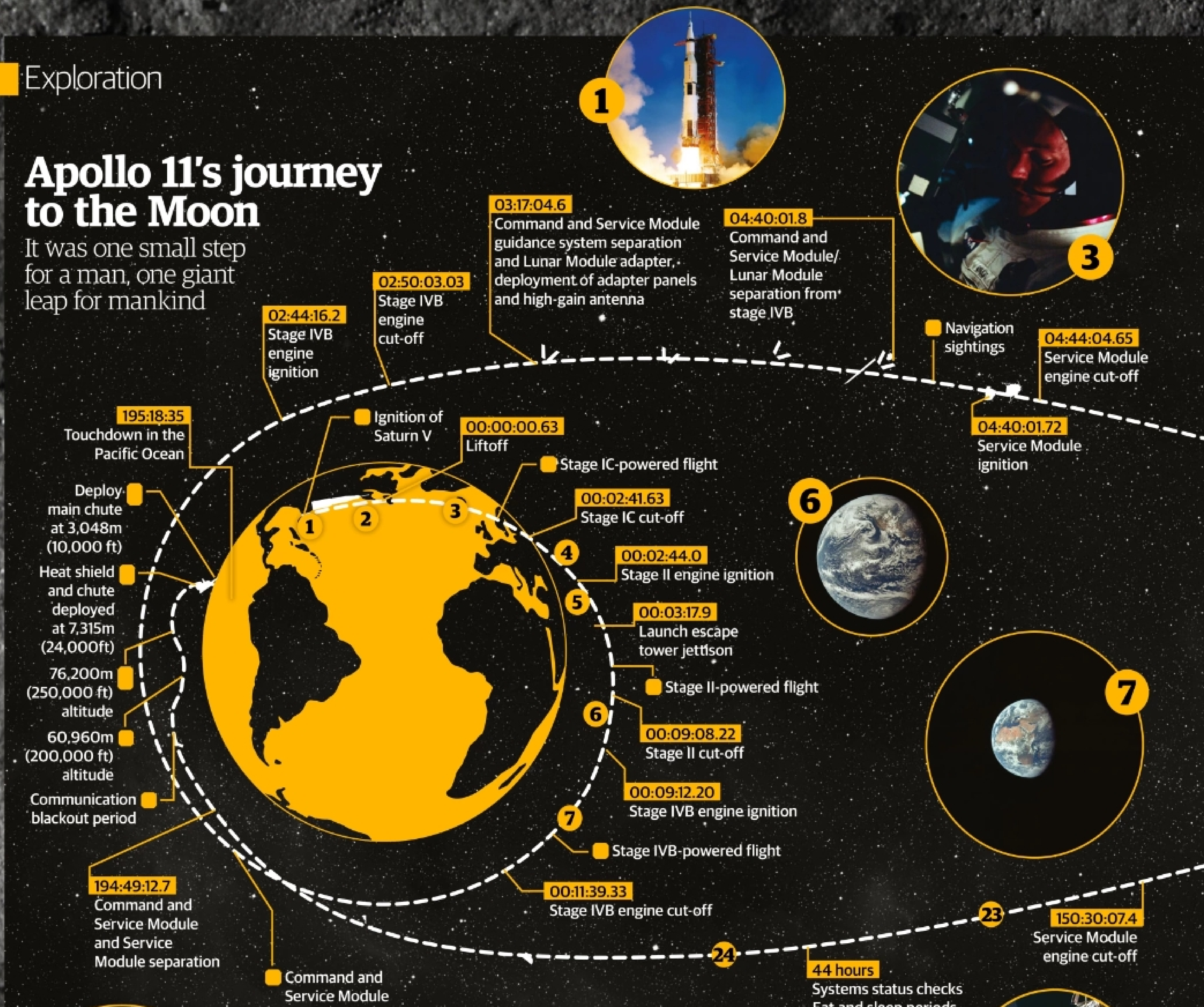
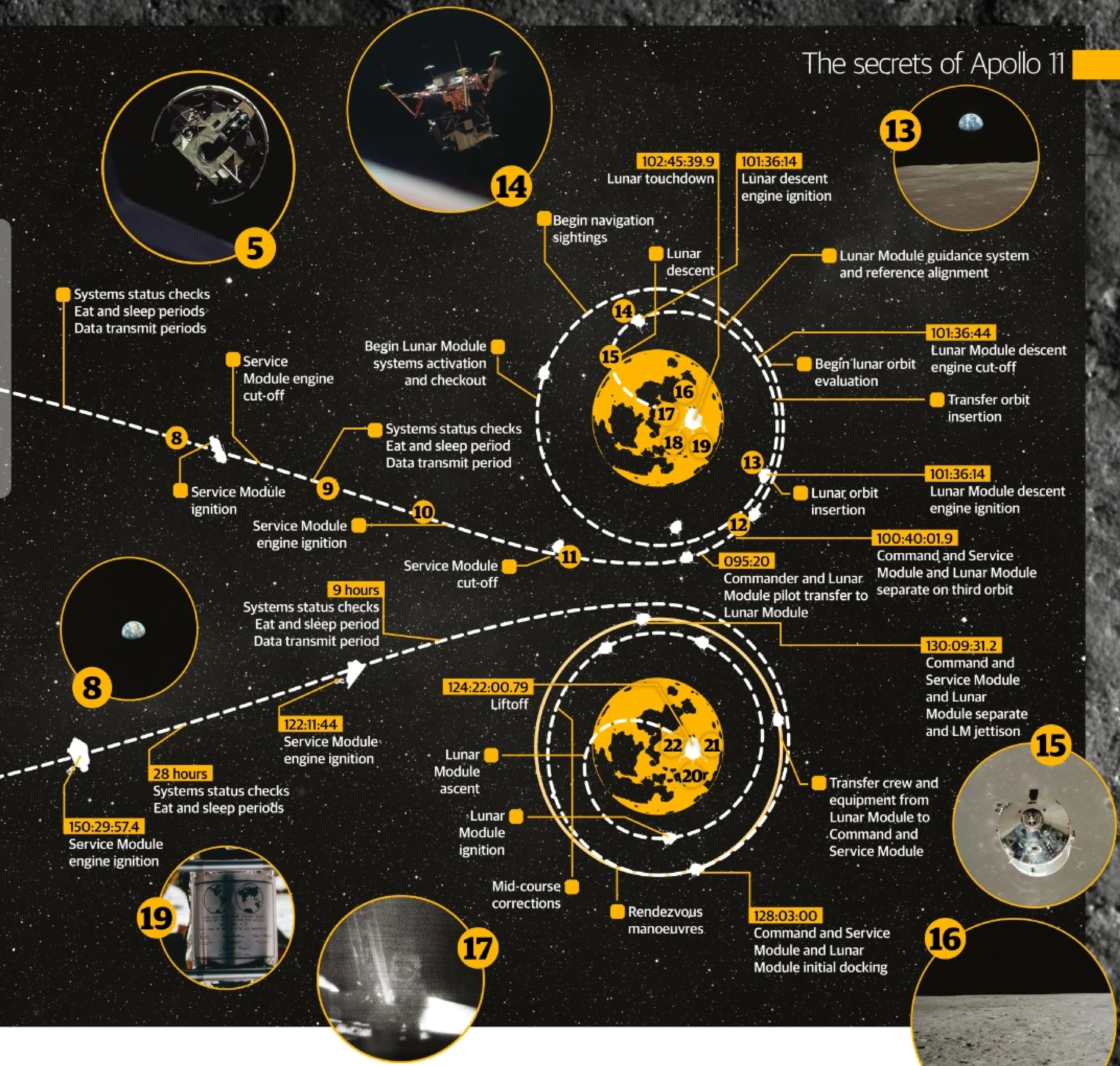
Apollo 11's journey to the Moon

It was one small step for a man, one giant leap for mankind


1
3
03:17:04.6
Command and Service Module guidance system separation and Lunar Module adapter, deployment of adapter panels and high-gain antenna
04:40:01.8
Command and Service Module/ Lunar Module separation from stage IVB
02:50:03.03
Stage IVB engine cut-off
02:44:16.2
Stage IVB engine ignition
Navigation sightings
04:44:04.65
Service Module engine cut-off
04:40:01.72
Service Module ignition
195:18:35
Touchdown in the Pacific Ocean
Ignition of Saturn V
00:00:00.63
Liftoff
Stage IC-powered flight
00:02:41.63
Stage IC cut-off
Deploy main chute at 3,048m (10,000 ft)
Heat shield and chute deployed at 7,315m (24,000ft)
76,200m (250,000 ft) altitude
60,960m (200,000 ft) altitude
Communication blackout period
1
2
3
4
00:02:44.0
Stage II engine ignition
5
00:03:17.9
Launch escape tower jettison
Stage II-powered flight
6
00:09:08.22
Stage II cut-off
00:09:12.20
Stage IVB engine ignition
7
Stage IVB-powered flight
00:11:39.33
Stage IVB engine cut-off
6
7
194:49:12.7
Command and Service Module and Service Module separation
Command and Service Module guidance system reference alignment
23
24
150:30:07.4
Service Module engine cut-off
44 hours
Systems status checks
Eat and sleep periods
Data transmit periods

disturbing and distracting and we didn't know what it meant."

The 1201 and 1202 alarms were obscure codes - and in effect the same error - that flashed up as Armstrong manually attempted to bring the Lunar Module down. Nobody seemed to know what the codes meant, except for two men: Jack Garman, a NASA computer engineer who had come across the codes before during a practice run, and Steve Bales, who was the Apollo guidance officer. The alarms were being caused by a problem with the landing radar that was stealing precious computing cycles, and the throttle control algorithm was barely working. The computer's 72kb of memory, barely enough to write a sentence in a modern word processor, was struggling as commands into it overflowed. Garman knew that it was safe to continue and allow the computer to handle matters.


5
14
13
102:45:39.9
Lunar touchdown
101:36:14
Lunar descent engine ignition
Begin navigation sightings
Lunar descent
Lunar Module guidance system and reference alignment
Systems status checks
Eat and sleep periods
Data transmit periods
Begin Lunar Module systems activation and checkout
Service Module engine cut-off
101:36:44
Lunar Module descent engine cut-off
Begin lunar orbit evaluation
Transfer orbit insertion
Systems status checks
Eat and sleep period
Data transmit period
8
9
10
11
12
13
14
15
16
17
18
19
Service Module ignition
Service Module engine ignition
101:36:14
Lunar Module descent engine ignition
Lunar orbit insertion
100:40:01.9
Command and Service Module and Lunar Module separate on third orbit
Service Module cut-off
095:20
Commander and Lunar Module pilot transfer to Lunar Module
9 hours
Systems status checks
Eat and sleep period
Data transmit period
8
130:09:31.2
Command and Service Module and Lunar Module separate and LM jettison
124:22:00.79
Liftoff
122:11:44
Service Module engine ignition
Lunar Module ascent
22
21
20r
15
28 hours
Systems status checks
Eat and sleep periods
Transfer crew and equipment from Lunar Module to Command and Service Module
150:29:57.4
Service Module engine ignition
Lunar Module ignition
Mid-course corrections
Rendezvous manoeuvres
128:03:00
Command and Service Module and Lunar Module initial docking
19
17
16

Its priority scheduling routines, which have formed some of the bases of a lot of modern code, were dumping lower priority tasks in favour of the ones critical to the lunar landing.

As the Eagle approached the surface on automatic, Armstrong and Aldrin realised that the scenery outside of the window didn't look familiar to them. "I think we may be a little long," commented Armstrong, referring to the Eagle having overshot its planned landing site. Looming ahead of them was a dangerous-looking boulder field, and coming down on any of those giant rocks the size of houses would have damaged or perhaps even destroyed the Eagle. Armstrong took manual control, using the thrusters to take the Eagle over the boulder field. But now fuel was running low and there was no turning back. Armstrong had to land the Eagle - somewhere, within minutes - or they would be out of fuel and crash. "We'd never been this close in training," said Kranz. "We started a stopwatch running, with a controller calling off seconds of fuel remaining."

If things were tense in mission control, on board the Eagle Armstrong and Aldrin had everything under control. With only 13 seconds of fuel left Apollo 11 made its safe landing in the Sea of Tranquillity. History had been made. "Houston, Tranquillity Base here," Armstrong radioed home. "The Eagle has landed."

In private, Aldrin took out a small cup, some wine and bread and said Holy Communion. The wine, under one-sixth Earth gravity, apparently curled up in the cup. After reading a section of the Gospel of St John, Aldrin said a few words, with Armstrong respectfully looking on. NASA had been threatened with legal action by Madalyn Murray O'Hair, an atheist, after the crew of Apollo 8 had read from the book of Genesis, so Aldrin's heartfelt ceremony

> "We felt that our survival was in the probability of 99 per cent. There were a lot of risks involved" Buzz Aldrin

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Your memories

"Apollo 11 is one of my first memories. I got to stay up late a few nights which was the big thrill at the time. I remember the fuzzy pictures on our black-and-white TV. It made me a life-long fan of space exploration."
James McGarry, @jmcgarry0

"I witnessed the launch on TV. The feeling I had was the whole world was watching with anticipation, pride and the reality… We are actually going to the Moon!"
Daniel Porter, @danielporter731

"Watched it all with a friend on a grainy TV up in their loft where the best signal [in the house] was. We were so aware of how absolutely extraordinary this was – and not so secretly hoping aliens would make an appearance!"
Suzanne Conboy-Hill, @strayficshion

"I was seven and just about remember it being on TV. I remember the landing and 'Live from the Moon' on screen. It was magical."
John Davies, @JohnnyD_cm

Left: The iconic photo of Aldrin standing on the surface, with Armstrong and the Lunar Module reflected in his visor

Bottom left: The flight controllers erupt into applause as Apollo 11 splashes down in the Pacific Ocean on 24 July 1969, successfully completing the mission

Bottom right: Aldrin smiles inside the Lunar Module never made it to the airwaves. Aldrin, though, has always been content in the thought that the first food and drink consumed on the lunar surface were communion items.

The original plan had been for the crew to get some sleep, but with that much adrenaline pumping through their veins that was never going to happen. At 02:39 UTC on the morning of 21 July, Armstrong made his way through the hatch and down the ladder before stepping foot on the surface of the Moon for the first time and saying those immortal words: "That's one small step for [a] man, one giant leap for mankind."

After exiting the Lunar Module, Armstrong and Aldrin only had a few hours to not only collect precious rock samples, but also deploy a series of experiments on the lunar surface. Solar wind experiments, a laser retro-reflector that is still used to this day to measure the Earth-Moon distance, seismometers and more were all deployed. Armstrong is cited as saying he felt like a five year old in a candy store, with not enough time to do all the things he wanted to. Standing on the Moon must have been an incredible experience. Aldrin described the scene around him as one of "magnificent desolation", adding that "you could look at the horizon and see very clearly because there was no atmosphere, ther was no haze or anything".

As Armstrong walked around setting up instruments and picking up rocks, Aldrin hopped around on the surface, testing what the best way to move about in the low gravity was. Most of the pictures taken during the landing are of Aldrin on the surface; barely half a dozen show Armstrong, and none clearly. That's because Armstrong had the camera for most of the Moon walk. While on the surface, the crew also had terrific problems with the American flag. It had a telescoping boom arm to hold it out in lieu of any wind to hold it up. The two astronauts wrestled to get the boom arm to extend fully, but it would not, so the flag had a small kink in it. They also found that it was almost impossible to get the flagpole to go deep enough into the ground and, in the end, they only just managed to get it to stay upright. Both of the crew worried it would fall over live on TV, and probably as President Nixon was on the phone to them. But it remained upright during the broadcasts and telephone calls.

After collecting their rocks and clambering back into the Lunar Module, the crew took off their boots and backpacks, and began to throw anything not of vital importance back onto the lunar surface. This included urine bags, empty food packs, empty cameras and so on. But to the crew, they were just getting in the way and not needed. There was time for one final crisis. The interior of the Lunar Module was cramped and, moving around in their bulky spacesuits, one of the astronauts had knocked out the switch for the circuit breaker that fired the ascent rocket that would take them home.

This was a real bottleneck moment for the mission. "If for some reason the ascent engine didn't work, there was no way to rescue the crew," said Kranz. Armstrong and Aldrin would be stranded on the Moon. The concern was so serious that President Nixon had a speech prepared, while mission control would close down communications with Armstrong and Aldrin after a clergyman had "condemned their souls to the deepest of the deep". Without that circuit breaker the crew were facing that lonely fate, but their training would not have allowed them to give up. "Rather than worry about things like that, we'd face them when the time came and we'd work as hard as we could to fix the problem until our oxygen ran out," said Aldrin.

In the end, the solution was remarkably simple. Jabbing the end of a pen into the slot where the broken switch had been, Aldrin was able to push the circuit breaker in. The ascent rocket fired and the two Moonwalkers were on their way home, via a rendezvous with Michael Collins in the Command Module.

As the Eagle took off, the flag finally did blow over, and to this day it lays flattened, bleached out by solar radiation.

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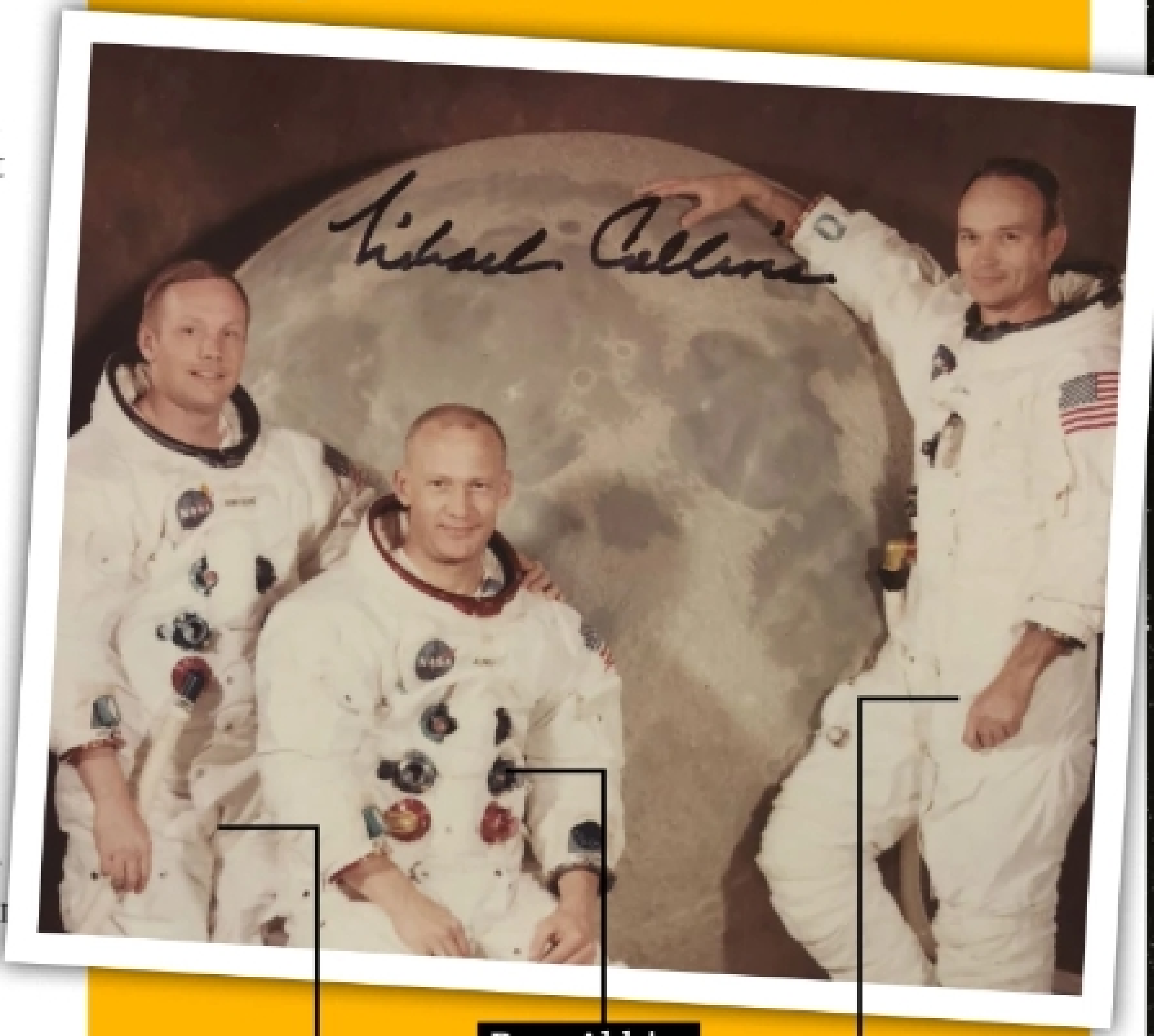
Michael Collins' forgotten photograph

The Apollo 11 Command Module pilot reveals an old photo he believes NASA never used



Buzz Aldrin,
Lunar Module pilot

Neil Armstrong,
commander

Michael Collins,
Command Module pilot

"Rather than worry, we'd face them when the time came and we'd work as hard as we could to fix the problem" Buzz Aldrin

"Neil could be very closed off emotionally"

James Hansen is the only author to write an official biography on space hero Neil Armstrong

"In some ways Neil was a very simple and very straightforward type of person, but at the same time very complex. That sounds like a contradiction, but the human personality is an amazing and difficult thing.

Neil could be very closed off emotionally in many respects, and very private and unwilling to share his inner thoughts. But at the same time – in certain social settings when he was comfortable, certainly around his fellow pilots and astronauts – he could be very friendly, had a great sense of humour and was just a great person to be around. I was interested in getting under his skin in a way. In writing the book, I didn't really want to turn it into a psychobiography where I try to apply psychology concepts to his personality. At the same time, I did want to understand what made him tick.

I'm a strong believer that the child is the father to the man. You have to really understand what goes on in childhood development, for example his parents, siblings, family and community, to really understand why a person becomes what they become."

5,498 DAYS ON MARS

OPPORTUNITY'S GREATEST HITS

It caused scientists to sing with joy as one breakthrough unfolded after another – we remember the best moments of Mars' longest-serving rover

Reported by David Crookes

For almost 15 years the Opportunity rover explored the Martian surface, helping scientists to make stunning breakthroughs and sending back tens of thousands of images which shone fresh light on the Red Planet. When it informed NASA that its batteries were running low, however, many feared the worst.

Despite sending over 1,000 commands, engineers from the Space Flight Operations Facility at NASA's Jet Propulsion Laboratory found they simply couldn't rouse the robot. A dust storm on Mars had proven too much, it seemed, and it ensured that as of 10 June 2018, nobody heard from Opportunity again.

But that's not to say the rover's memory doesn't live on. Its value to science has been huge and it appears rather apt that it would fail at Perseverance Valley, given its longevity. Poignantly, the final attempt to wake it came with a rendition of the Billie Holiday song, *I'll be seeing you*. Here we look at its greatest moments since 2004.

© NASA/JPL-Caltech;

OPPORTUNITY'S MAIN GOALS

☑ To last three months
Opportunity's mission should have lasted 92.5 Earth days – it went on for 5,498!

☑ Find past water activity
Opportunity was to look for and analyse soil and rocks for signs of water.

☑ Figure rock, mineral and soil composition
It determined the composition and distribution of these materials at its landing site – and further afield.

☑ Determine geologic processes
Opportunity studied the geology of more than 100 impact craters and examined their formation and erosion.

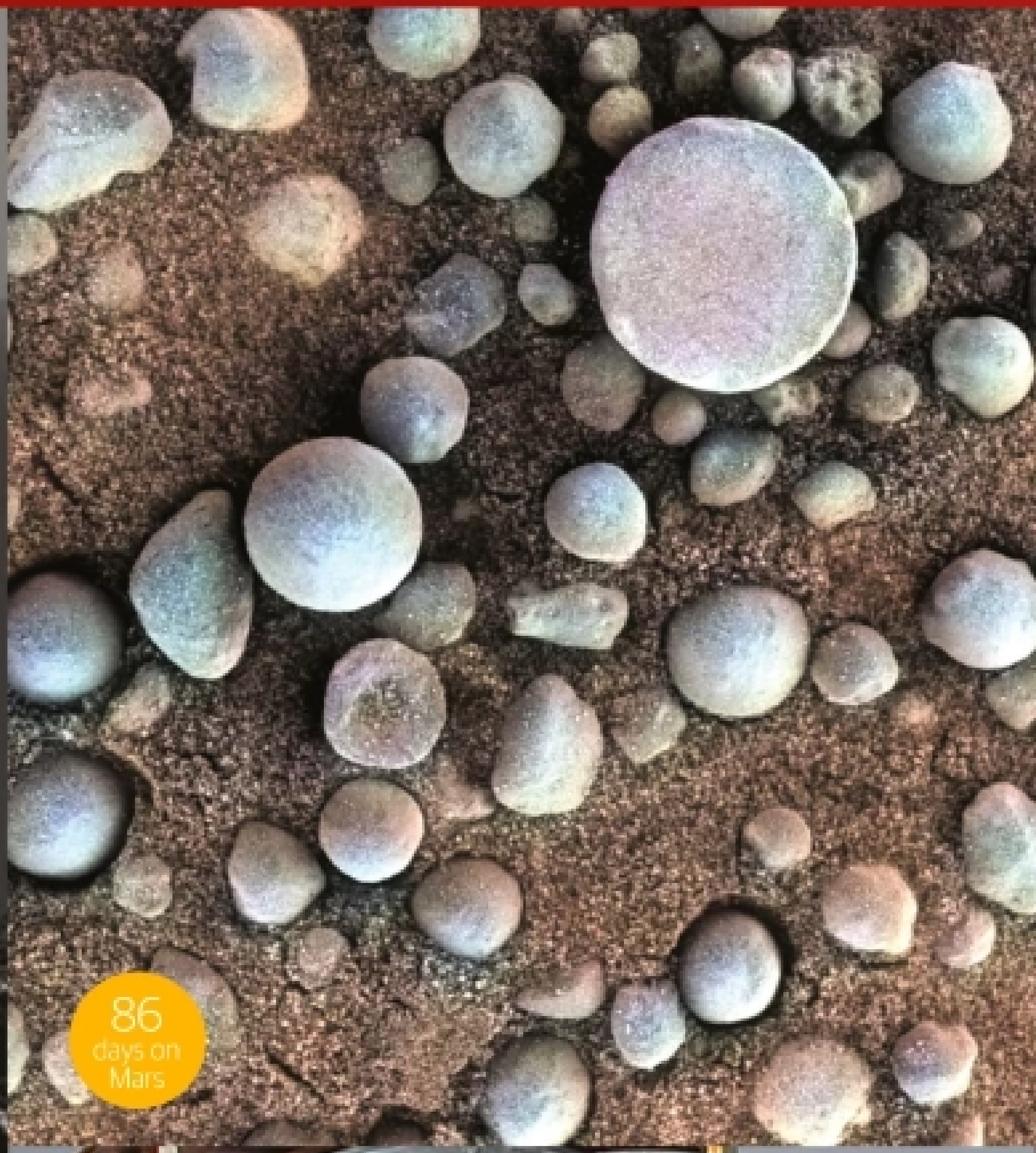
☑ Validate observations made by orbiter
The rover could use its many instruments to collect and study samples, confirming what the Mars Reconnaissance Orbiter had observed.

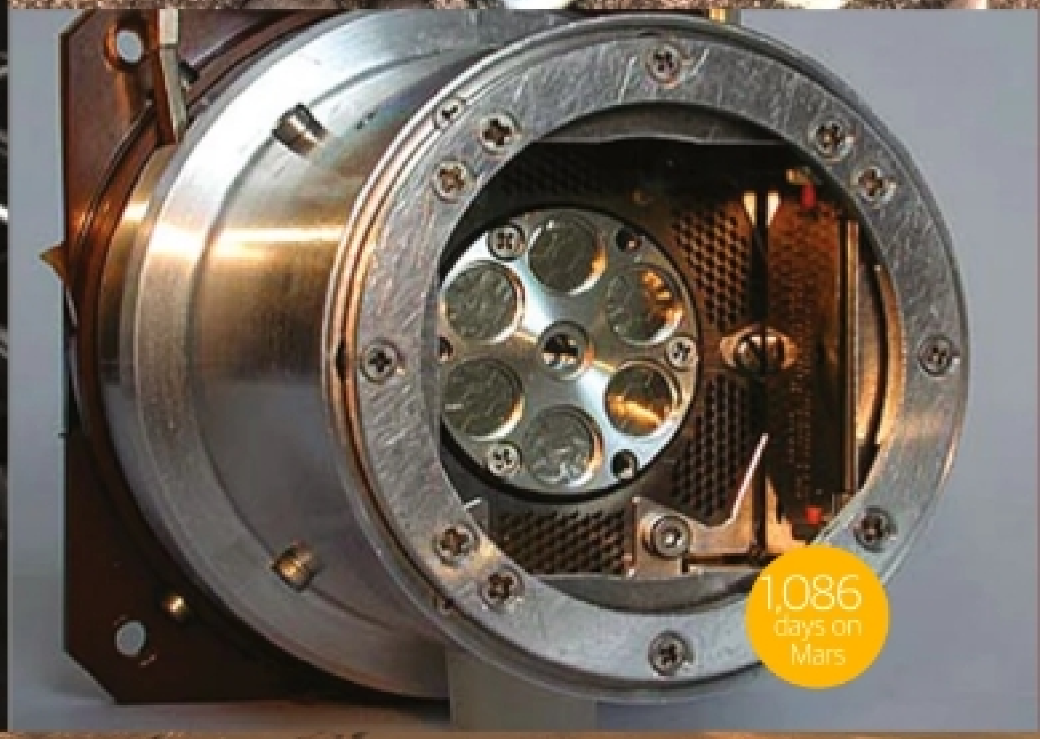
☑ Search for iron-containing minerals
Opportunity found rocks rich in iron and magnesium at Comanche.

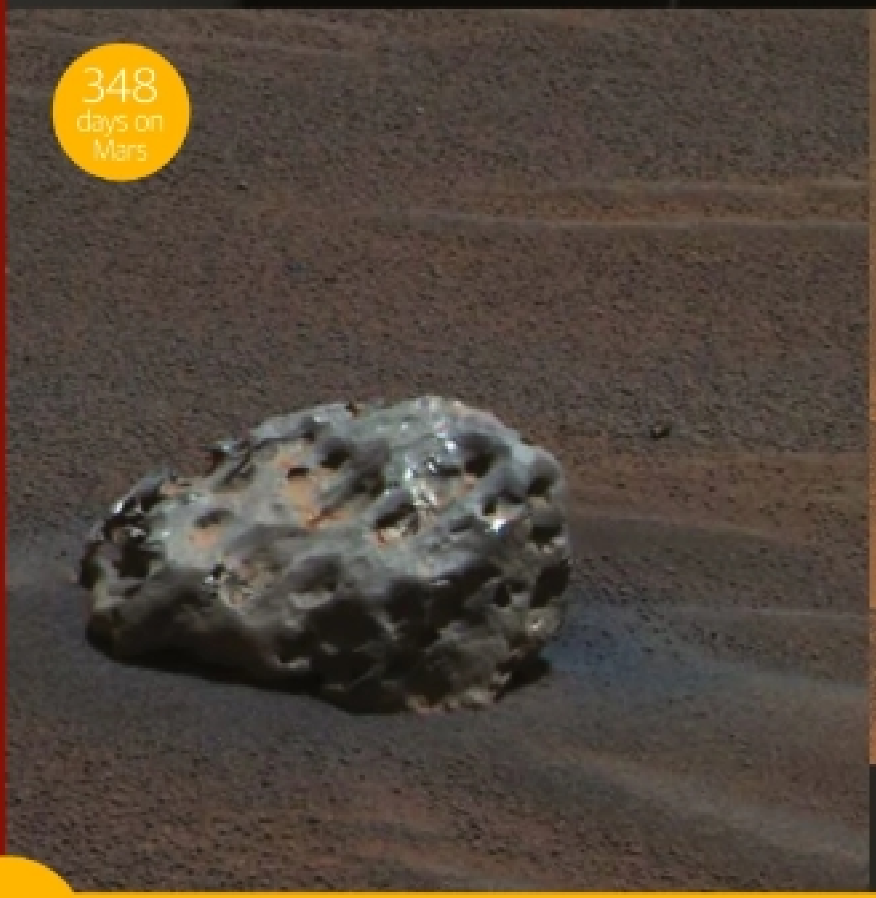
☑ Characterise rock and soil mineralogy
Straight away Opportunity discovered hematite, and it went on to make more breakthroughs.

☑ Discover environmental conditions
The composition of the rocks gave strong clues as to the make-up of the atmosphere when water was present.

☑ Work out potential for life
Many of the discoveries by Opportunity pointed towards the likelihood that Mars could have supported life.







25 JANUARY 2004

Days on Mars: 1

Simply landing was a major feat, and the fact Opportunity followed its twin Spirit rover three weeks earlier was really quite remarkable. It touched down on a smooth-flat plain on the opposite side of Mars to Spirit, having approached the surface at more than 19,000 kilometres (12,000 miles) per hour. It was soon sending images back and trundling along the surface.

2 MARCH 2004

Days on Mars: 38

Opportunity's imaging at its landing site in Eagle's rim provided the first close-up view of finely layered sedimentary rocks on Mars, a major breakthrough since it showed liquid water had pooled on the surface at some point. The rocks "clearly preserve a record of environmental conditions different from any on Mars today," Dr Steve Squyres said.

19 APRIL 2004

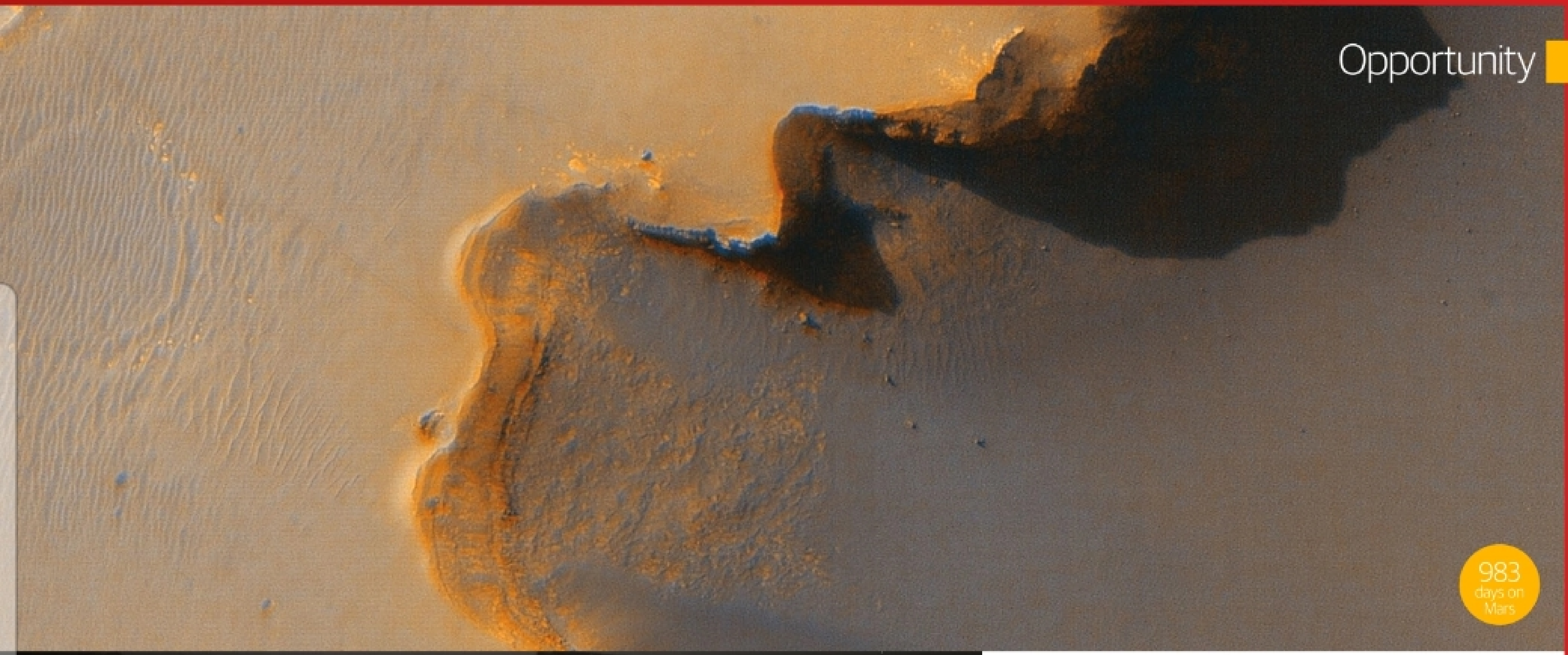
Days on Mars: 86

Groups of grey-blue mineral spheres were examined by Opportunity's composition-reading Mössbauer spectrometer. Scientists found they contained hematite, providing early evidence of a history of water on the Red Planet since it's typically found in places on Earth where standing water or mineral hot springs were once present.

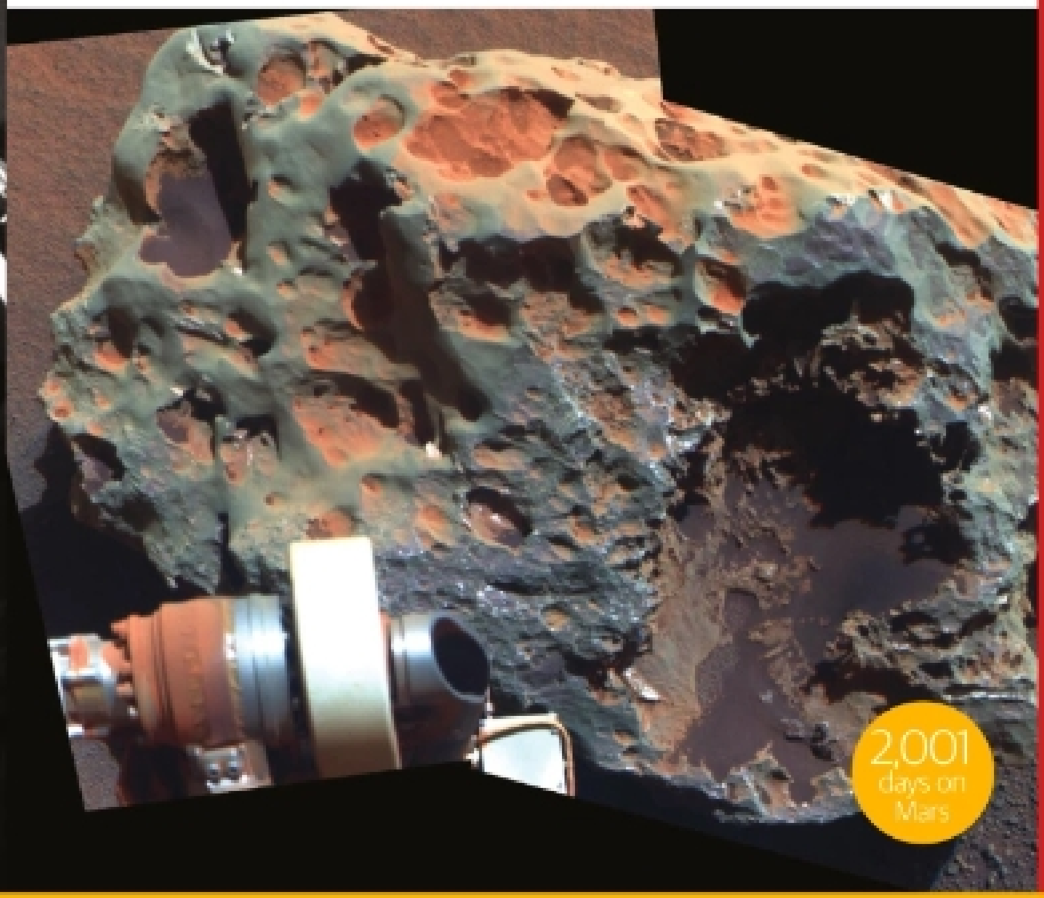
6 JANUARY 2005

Days on Mars: 348

Opportunity discovered a pitted meteorite the size of a basketball in a cratered flatland of Mars called Meridiani Planum and found it was mostly made of iron and nickel. Since it was located close to debris from Opportunity's heat shield it became known as Heat Shield Rock, and it was the first meteorite ever spotted on another planet.



> “I cannot think of a more appropriate place for Opportunity to endure on the surface of Mars than one called Perseverance Valley”
>
> **Michael Watkins, director of JPL**



20 MAY 2005

Days on Mars: 480

A rover's life is never a simple one. Although it set a distance record for one-day travel when it trundled along for 177.5 metres (582 feet) on 19 February 2005, come April it had become stuck in a sand dune, with its wheels buried rim-deep. Following numerous simulations on Earth, drive commands issued to the rover eventually set it free.

3 OCTOBER 2006

Days on Mars: 983

Having already explored layered rocks in cliffs around Victoria Crater, Opportunity began to make its way down a slope to better investigate the textures and compositions of exposed materials. It was risky: there was every chance Opportunity wouldn't make it back out. It re-emerged in August 2008 having successfully studied the stratigraphy inside.

13 JANUARY 2007

Days on Mars: 1,086

Rather than measuring the chemical content of rocks and dust on the ground, Opportunity began to use its Alpha Particle X-ray Spectrometer to detect the amount of argon in Mars' atmosphere. With Spirit doing the same, the two rovers could determine the atmospheric mixing processes between the polar air and the air at the tropics over time.

17 JULY 2009

Days on Mars: 2,001

Three iron meteorites were found by Opportunity over a small area on Meridiani Planum: Block Island, Shelter Island and Mackinac Island. The first was found in July and it appears to have smashed into the Red Planet's surface in the Noachian period. Block Island was the size of a small ice chest and is thought to have weighed half a ton.

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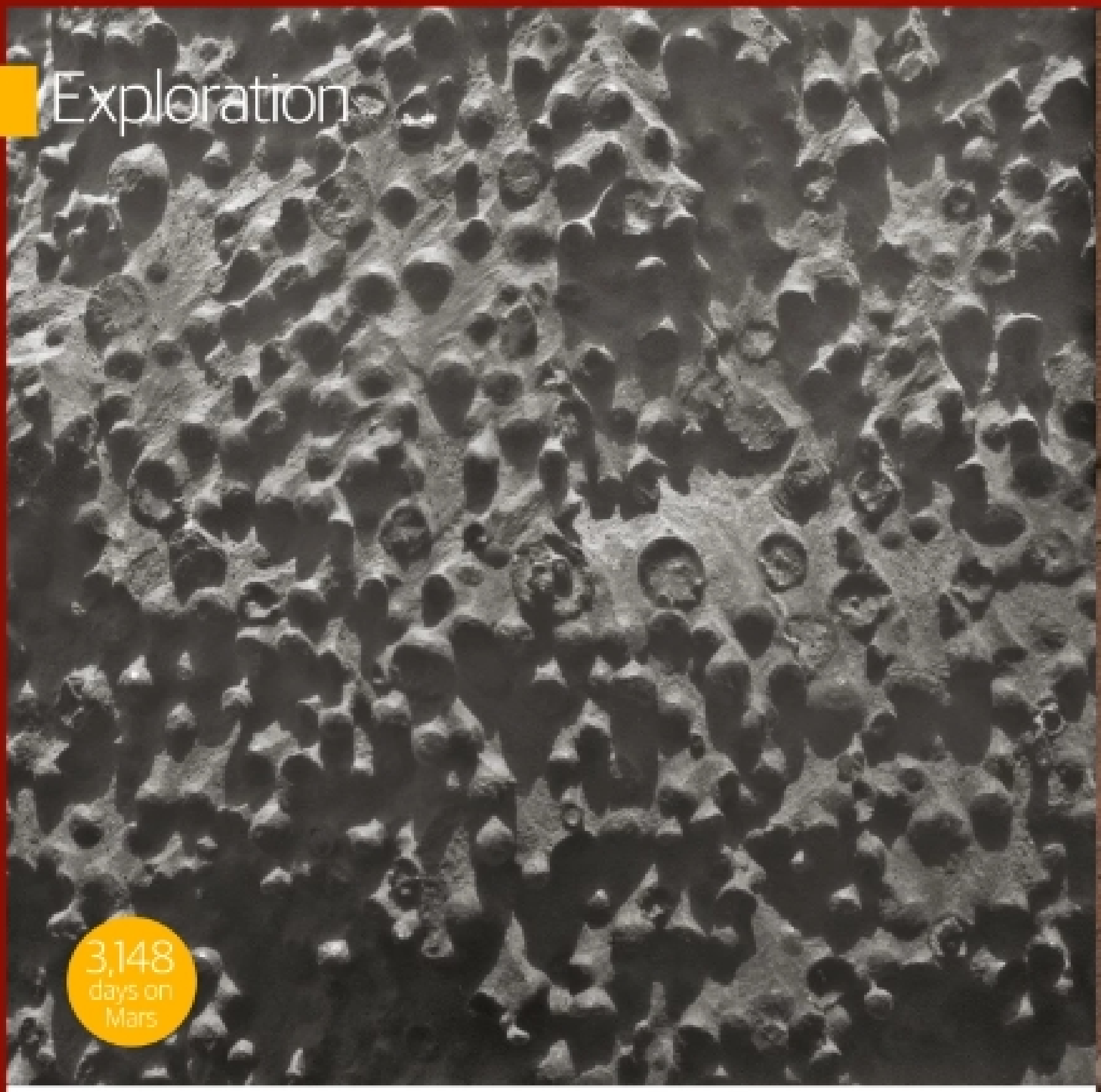
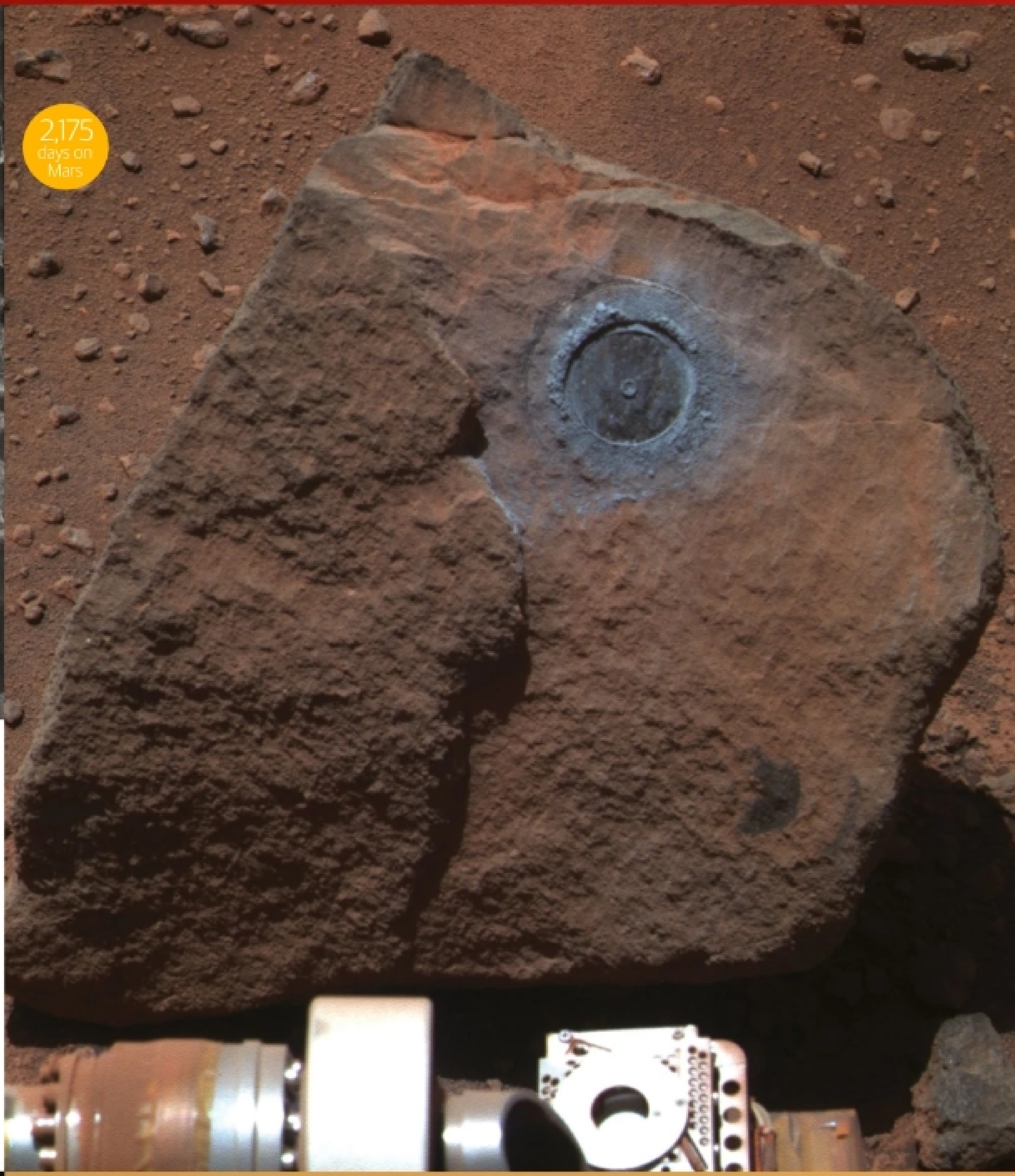
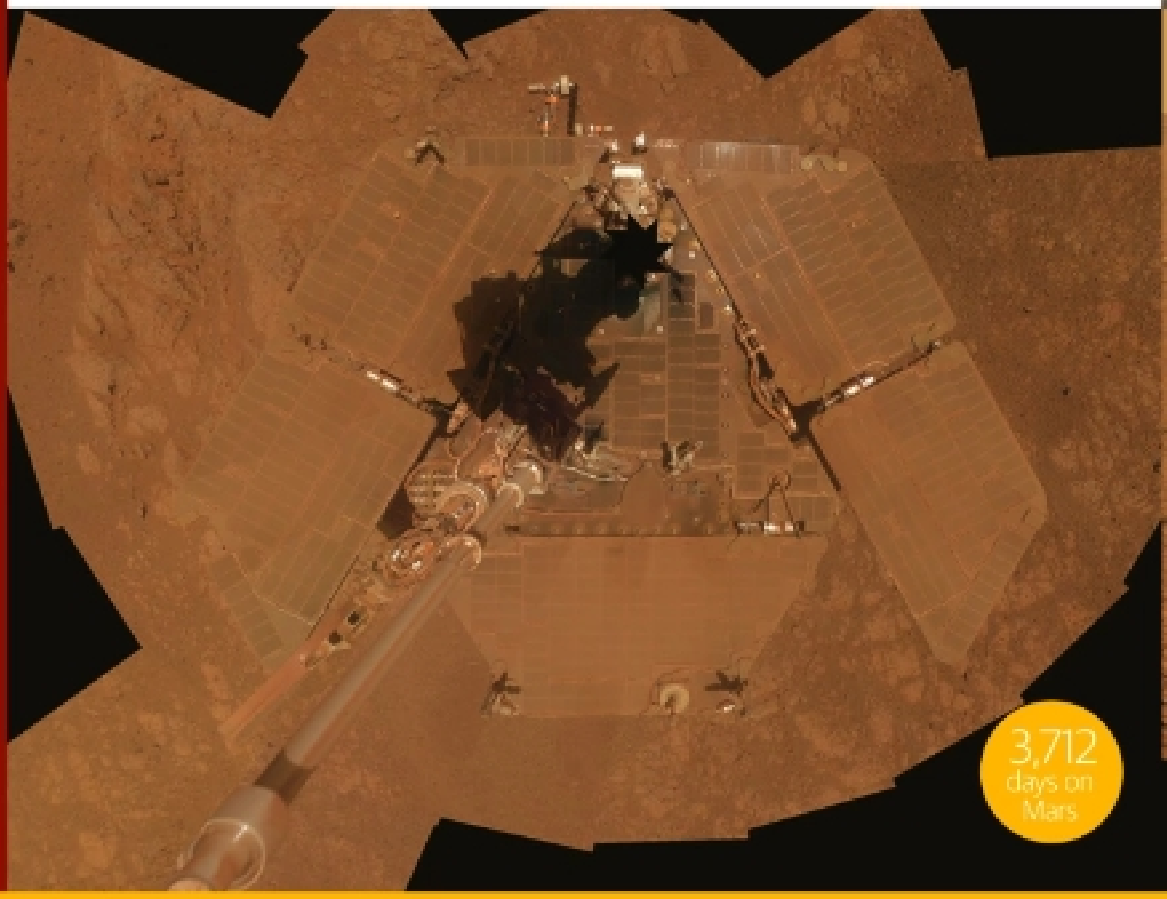




> "It is because of trailblazing missions such as Opportunity that there will come a day when our brave astronauts will walk on the surface of Mars"
>
> **Jim Bridenstine, NASA administrator**



6 JANUARY 2010

Days on Mars: 2,175

A rock named 'Marquette Island' was discovered by Opportunity, and it was particularly intriguing because it was unlike any other rock found on Mars, with a different composition and character to the others. Geologists figured it had originated from within Mars' crust due to its coarse texture, pointing towards a slow cooling time.

15 JULY 2010

Days on Mars: 2,364

Even though the Spirit rover had seen many dust devils, they had eluded Opportunity for more than six years. So when its panoramic camera caught sight of one it made for an interesting observation. Indeed, it was hoped another dust devil could help bring Opportunity back to life by blowing dust from its solar arrays eight years later.

7 NOVEMBER 2011

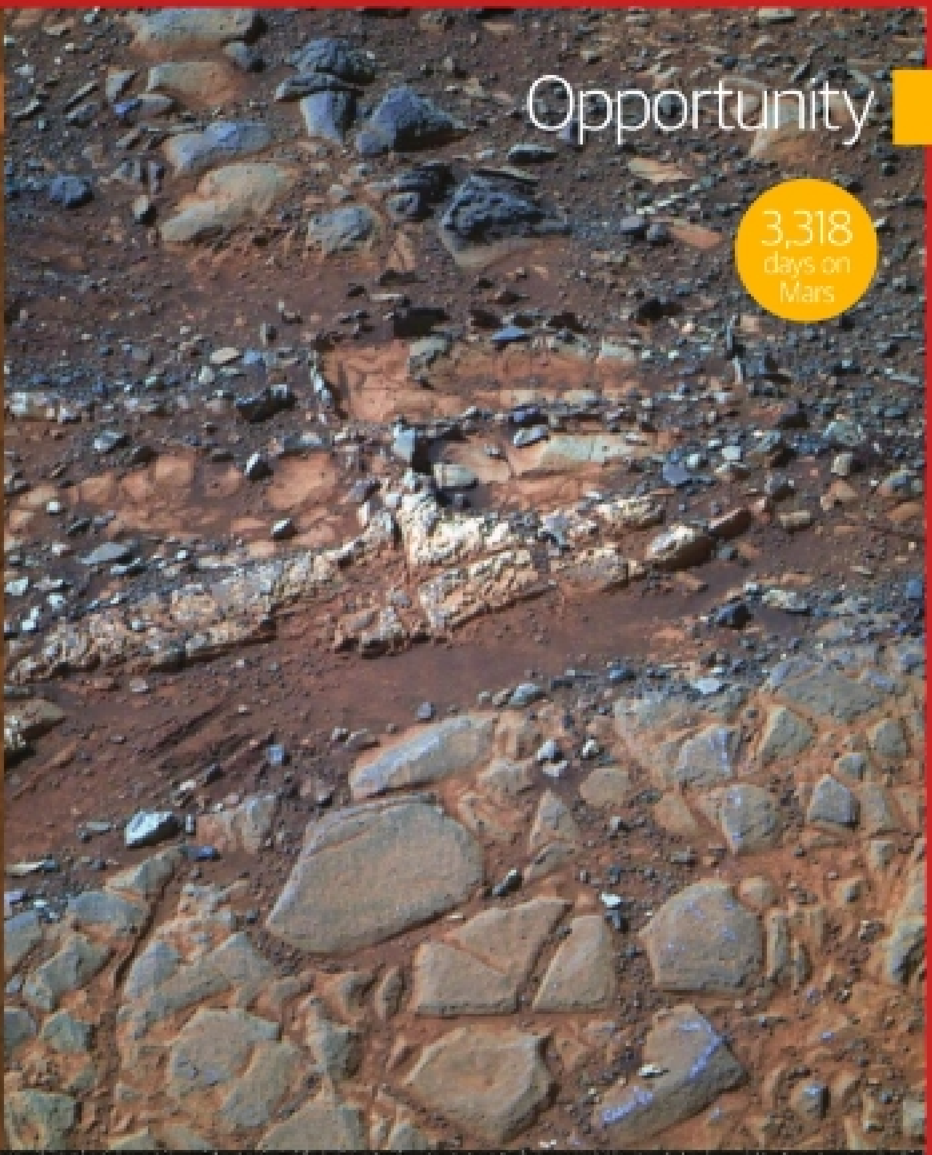
Days on Mars: 2,845

Opportunity had travelled for 32 kilometres (20 miles) before it found bright veins of a mineral called gypsum on a section of Endeavour Crater's rim. They were an indication that water had flowed through underground fractures in rocks. They would have formed when calcium sulphate associated with water.

6 SEPTEMBER 2012

Days on Mars: 3,148

Opportunity took an image of a baffling set of spheres that each measured up to three millimetres across at an outcrop called Kirkwood in the Cape York segment of the western rim of Endeavour Crater. They certainly kept scientists busy, and they were different to the similar-looking spheres found in 2004 since they lacked a high iron content.



23 FEBRUARY 2013

Days on Mars: 3,318

Analyses of ancient clays close to the rim of the Endeavour Crater suggested mild, pH-neutral water had formed between 4.1 and 3.7 billion years ago. Based on the study of a clay mineral called smectite that is rich in aluminium in that location by Opportunity, it pointed towards favourable conditions for ancient microbial life.

22–24 MARCH 2014

Days on Mars: 3,712

There's nothing like a good refresh, and Opportunity certainly benefited when a windswept winter blew its solar panels clean of much debris. Boosted by an increase in solar energy, engineers were able to make use of the power to send it on its way to Murray Ridge on Endeavour Crater. A selfie captured the stark difference the wind made.

7–19 JUNE 2017

Days on Mars: 4,896

In a first for a Martian rover, Opportunity began to drive down a gully carved by a fluid with the aim of getting inside the Endeavour Crater. Scientists wanted to draw comparisons between the rocks found on the plains and in the crater while searching for rocks that predated the crater's formation.

10 JUNE 2018

Days on Mars: 5,251

Opportunity took more than 215,000 images during its time on Mars, but this is perhaps the most poignant because it's the very last one. Snapped as a dust storm blighted the Red Planet for months, the resulting lack of light to its solar panels ensured it never woke from its safe mode. NASA finally decided on 13 February 2019 to give up hope.

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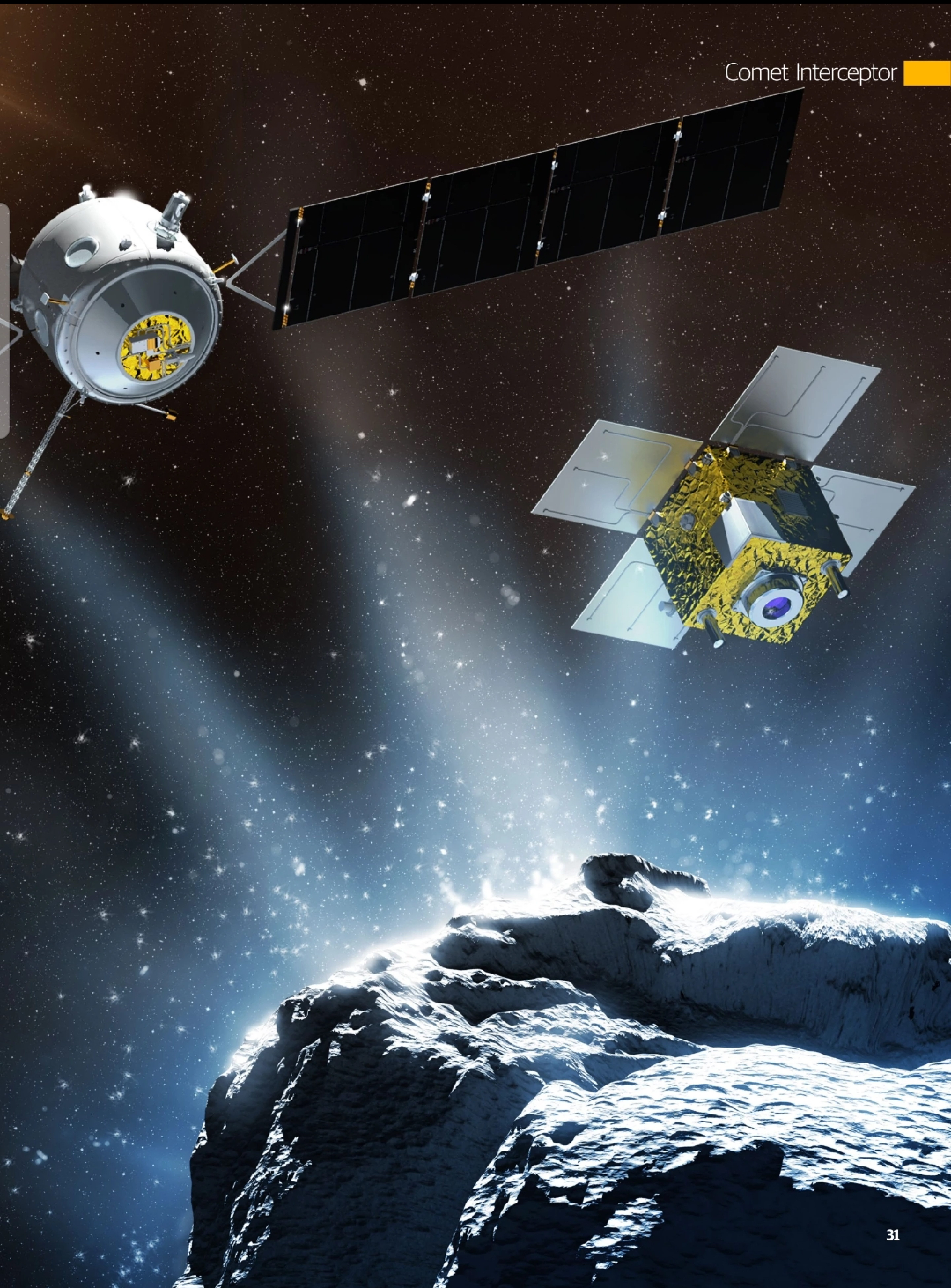
MISSION TO CATCH A COMET

Comet Interceptor will make history by visiting a distant 'space snowball' - or an interstellar object

Reported by Jonathan O'Callaghan

© Illustration by Adrian Mann



Every so often in our Solar System, a comet swings in from the outer reaches and makes a brief visit to the inner portion of the system before heading out again – either on a long sweeping orbit, or never to be seen again. Such comets, known as long-period comets, are of great interest to scientists, but we've only ever seen them from afar. What if we could see one up close?

That's the idea behind a new mission called Comet Interceptor, which in June 2019 was selected by the European Space Agency (ESA) for further development, with a potential launch planned in 2028. The mission will be unprecedented, launching with no particular target in mind, but instead waiting in space for a suitable comet to approach from the Oort Cloud, the vast array of trillions of comets thought to surround our Solar System. If one gets nudged from its orbit and does approach – and it's hoped it will – the spacecraft will race off and fly past, returning images and data to Earth in the process.

"It's a unique target," says Dr Colin Snodgrass from the University of Edinburgh in the UK, the deputy lead on the Comet Interceptor mission proposal. "Going to a dynamically new comet from the Oort Cloud is something we've never done before. And it's something we couldn't normally conceive of doing, because these comets are discovered a couple of months or years before they come past, and that's too short to launch a mission. So it's unique because we're able to wait in space and intercept this new target."

Comet Interceptor is known as an F-class mission, or 'fast' mission. This isn't in reference to its plans in space, but rather its development time. Having been selected, the team will now plan to have the mission ready to launch in eight years. The mission will have a mass of less than 1,000 kilograms and will head to space in 2028 as a secondary mission on launch of the Atmospheric Remote-sensing Infrared Exoplanet Large-survey (ARIEL) telescope, designed to hunt for planets beyond the Solar System.

The two missions will be sent 1.5 million kilometres (1 million miles) from Earth beyond the Moon, to a location known as Lagrange point 2 (L2). Here the gravity of the Moon and Earth essentially cancel out, allowing spacecraft to remain in one position in space without expending too much fuel. While ARIEL will be deployed here permanently to look for exoplanets, Comet Interceptor will be ready and waiting for its mission to begin.

In the build-up to the mission, and after its launch if necessary, the team will be keeping a very close eye on the skies to look for potential targets to visit. They will make use of vast surveys of the sky like the Large Synoptic Survey Telescope (LSST) in Chile, which will switch on in 2020, to look for any long-period comets entering the Solar System. The team will be on the hunt for a comet that approaches roughly to Earth's orbital plane, which would make an interception possible.

"It has to get close to Earth's orbit," says Snodgrass. "It doesn't necessarily have to get close to Earth, but it has to come to about one

Right (clockwise): In 2014 Europe's last comet mission, Rosetta, entered orbit around Comet 67P/Churyumov-Gerasimenko, ending in 2016

Comet 73P/Schwassmann-Wachmann 3, which has broken apart, is a backup target for Comet Interceptor

Comets may have brought water, and even life, to Earth early in its history

© ESA

Why study a comet?

What we can learn about these icy bodies as they make their way around the Sun

Water, water everywhere

Comets contain vast amounts of water-ice, both on their surface and underground. We think they may have been responsible for delivering water to Earth in its past, so studying them can tell us more about whether this is true or not.

Origins of life

It's also thought that comets may contain some of the key ingredients for life, such as amino acids. Again, like water, it's possible that these ingredients were brought to the young Earth by comets hitting our planet – perhaps giving rise to all life as we know it!

The giant planets

As comets are icy, they likely formed in the Solar System's outer reaches early in its history. This is the same location that some of our larger planets like Saturn and Neptune are thought to have formed, so by studying comets we can learn more about those worlds.

Why are they different?

If all comets formed in the outer Solar System, you would expect them to be mostly the same. But we are rapidly finding that is not the case, with many comets having unique compositions and abundances of water. Finding out why is key to understanding the Solar System's evolution.

Could one hit Earth?

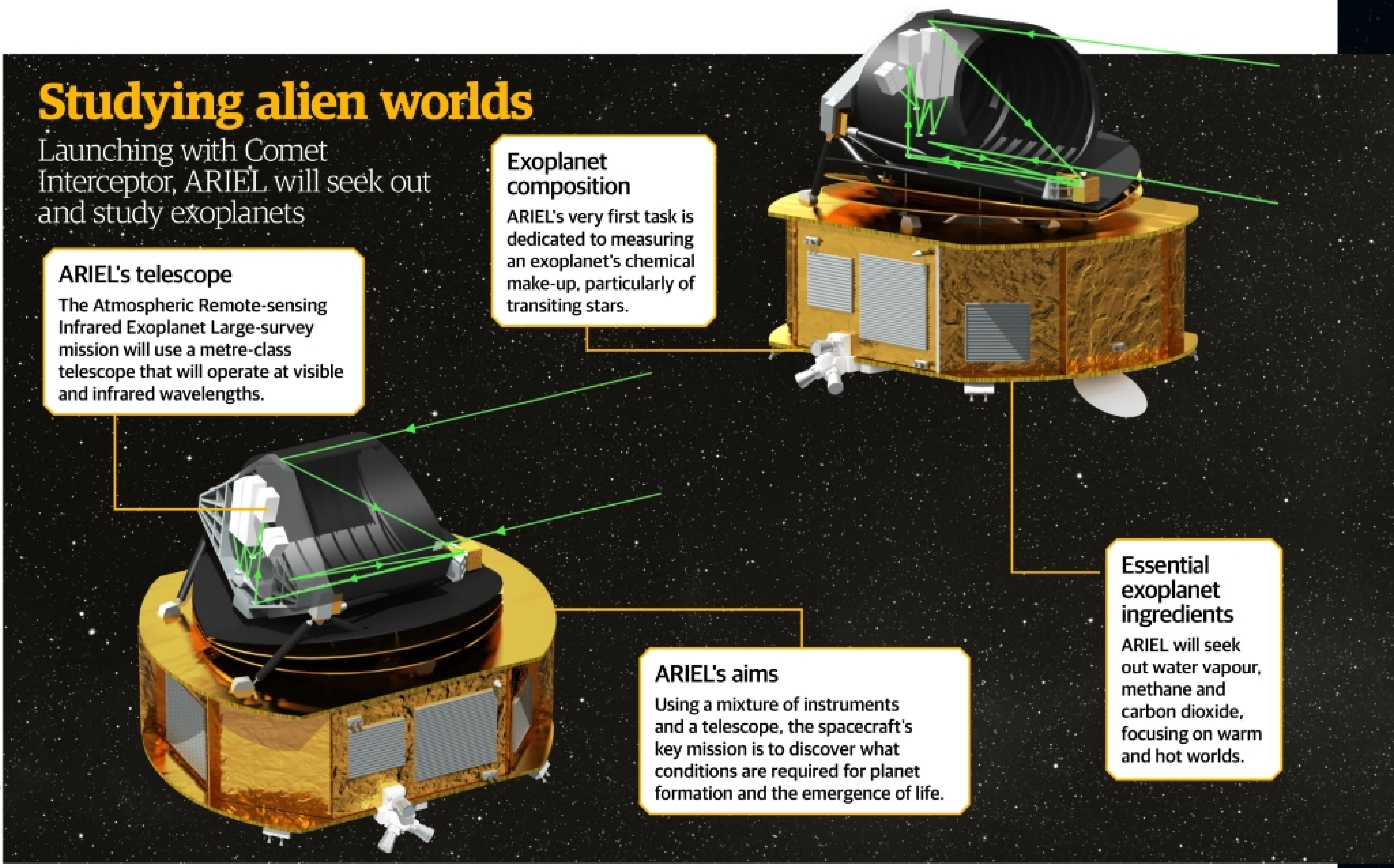
A comet is thought to have wiped out the dinosaurs 66 million years ago, but could such an event occur again? Finding comets can help us look for any that might be on a collision course with Earth – although so far, the coast is clear.

Science in action!

Comets are fascinating laboratories of science where we can see some amazing processes taking place. As they approach the Sun they form large tails that extend long behind them as they become more active. Studying them is quite simply scientifically interesting!

Studying alien worlds

Launching with Comet Interceptor, ARIEL will seek out and study exoplanets



ARIEL's telescope

The Atmospheric Remote-sensing Infrared Exoplanet Large-survey mission will use a metre-class telescope that will operate at visible and infrared wavelengths.

Exoplanet composition

ARIEL's very first task is dedicated to measuring an exoplanet's chemical make-up, particularly of transiting stars.

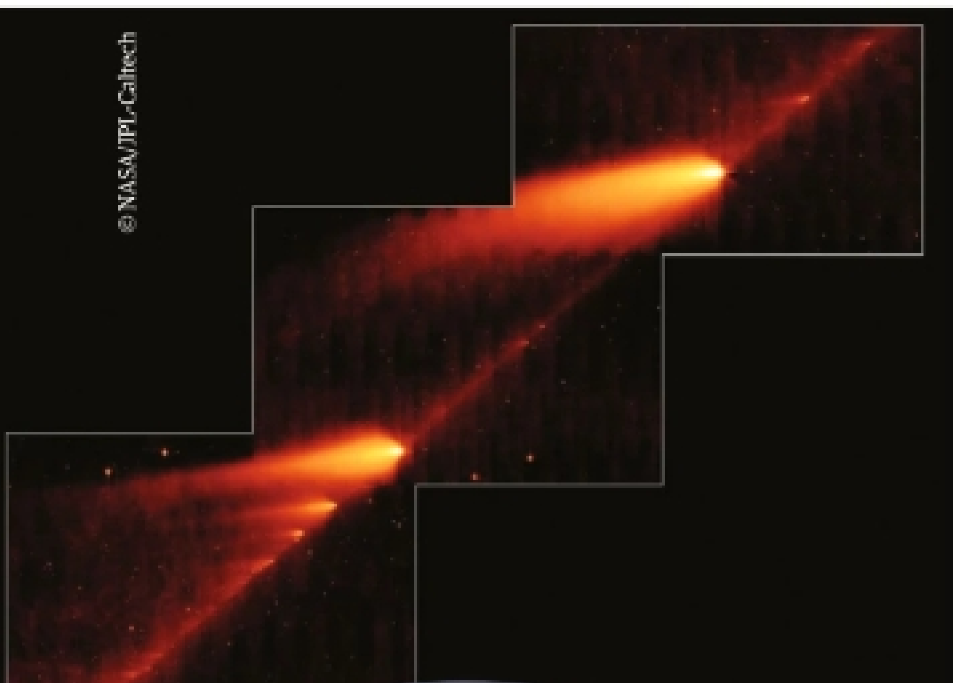
ARIEL's aims

Using a mixture of instruments and a telescope, the spacecraft's key mission is to discover what conditions are required for planet formation and the emergence of life.

Essential exoplanet ingredients

ARIEL will seek out water vapour, methane and carbon dioxide, focusing on warm and hot worlds.

© Illustration by Adrian Mann



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> "Going to a dynamically new comet from the Oort Cloud is something we've never done before" **Dr Colin Snodgrass**

astronomical unit from the Sun, so the same distance that we are from the Sun. It could be around the other side of the Sun, although we would prefer it not to be because we want to be able to see it with Earth telescopes at the same time."

Once a target is spotted, Comet Interceptor will leave its position at L2 and make its way towards it, likely taking several months or years to reach the target. Once it reaches its target, however, it will not be able to enter orbit – like the ESA's Rosetta mission did around Comet 67P in 2014 – owing to the great velocities involved. Instead it will merely fly past, using a suite of instruments to study the comet as it does so – including mapping its surface, snapping images and measuring its composition.

The flyby will last just a matter of minutes, and the main spacecraft will likely fly past at a distance of about 1,000 kilometres (600 miles). This is because as the comet approaches the Sun for the first time, it is likely to become very active as its icy surface melts, throwing lots of debris into space into a coma that surrounds the comet's solid nucleus that could damage the spacecraft. However, to get a closer look Comet Interceptor will also carry with it two smaller spacecraft, which will be sent much closer to the comet.

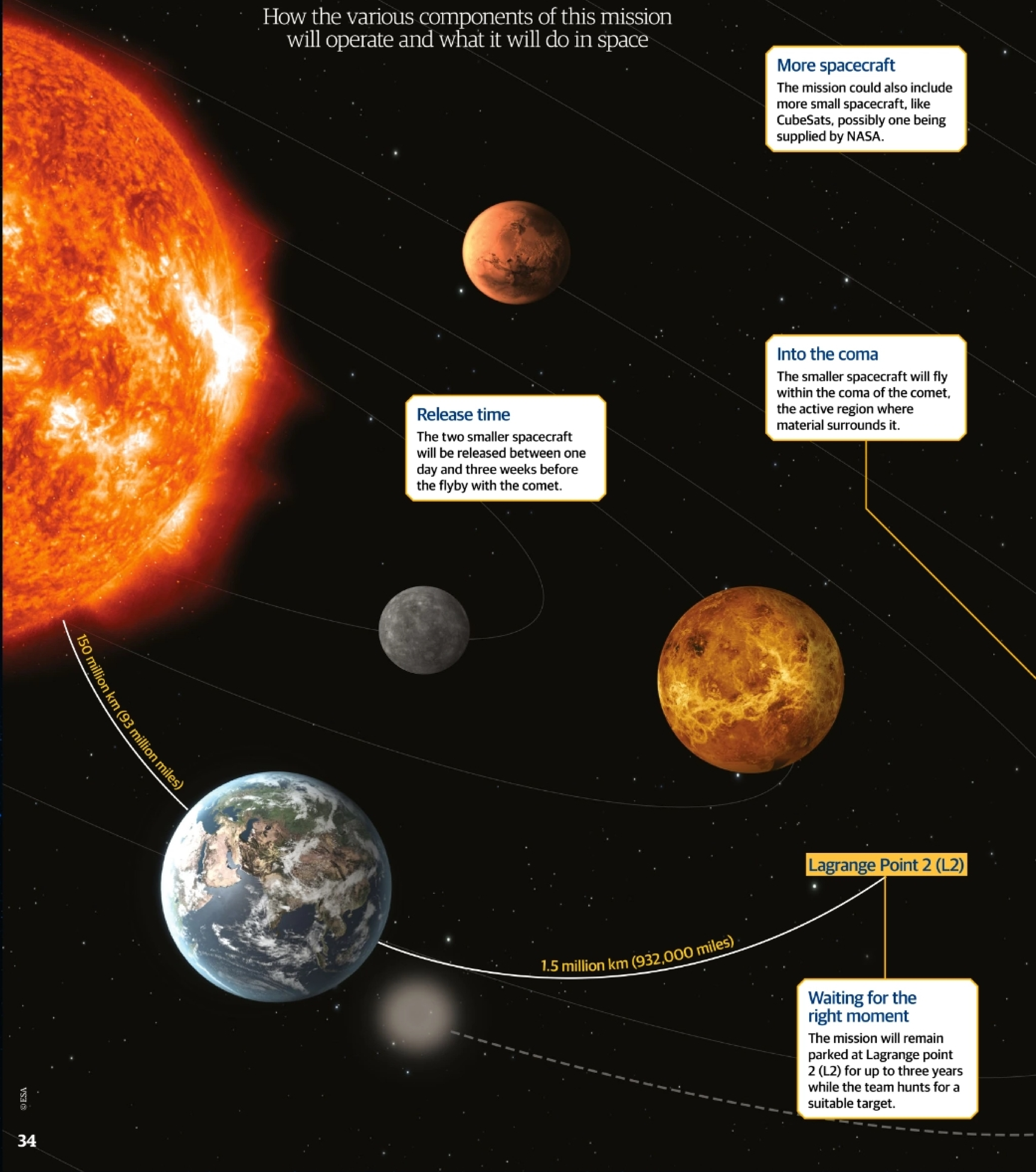
These will be equipped with shields at their front to deflect debris, and will be sent on much riskier excursions near the comet. They are more expendable than the main mothership, so the team will be more willing to take risks with them and send them closer to get better views and data. These smaller spacecraft have only been named B1 and B2 so far – and one of them will be built by the Japanese space agency, JAXA – while the larger spacecraft has only been named A for now.

Studying a long-period comet like this close-up for the first time has lots of interesting possibilities. While we have sent many spacecraft to comets before, including the aforementioned Rosetta mission, these have all been short-period comets. As these regularly orbit the Sun, their surfaces have been dramatically altered over time. Looking at a long-period comet, however, could give us a glimpse back into the dawn of the Solar System itself, and perhaps provide hints as to the origin of water and even life on Earth.

"Long-period comets are the ones that have orbits over 200 years," said research assistant Dr Ashley King, an expert in asteroids and comets from the Natural History Museum in London. "They tend to have really elliptical orbits, and these things come

Comet Interceptor: how it will work

How the various components of this mission will operate and what it will do in space


150 million km (93 million miles)
1.5 million km (932,000 miles)
Lagrange Point 2 (L2)

More spacecraft
The mission could also include more small spacecraft, like CubeSats, possibly one being supplied by NASA.

Into the coma
The smaller spacecraft will fly within the coma of the comet, the active region where material surrounds it.

Release time
The two smaller spacecraft will be released between one day and three weeks before the flyby with the comet.

Waiting for the right moment
The mission will remain parked at Lagrange point 2 (L2) for up to three years while the team hunts for a suitable target.

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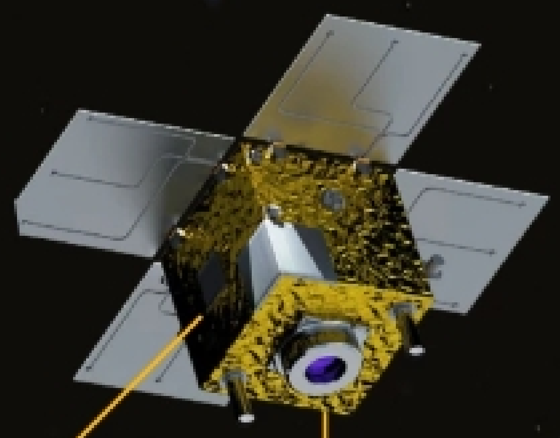


Size of the spacecraft

Comet Interceptor will weigh about 850 kilograms (1,900 pounds) in total, comprising all three spacecraft.

Plasma and atoms

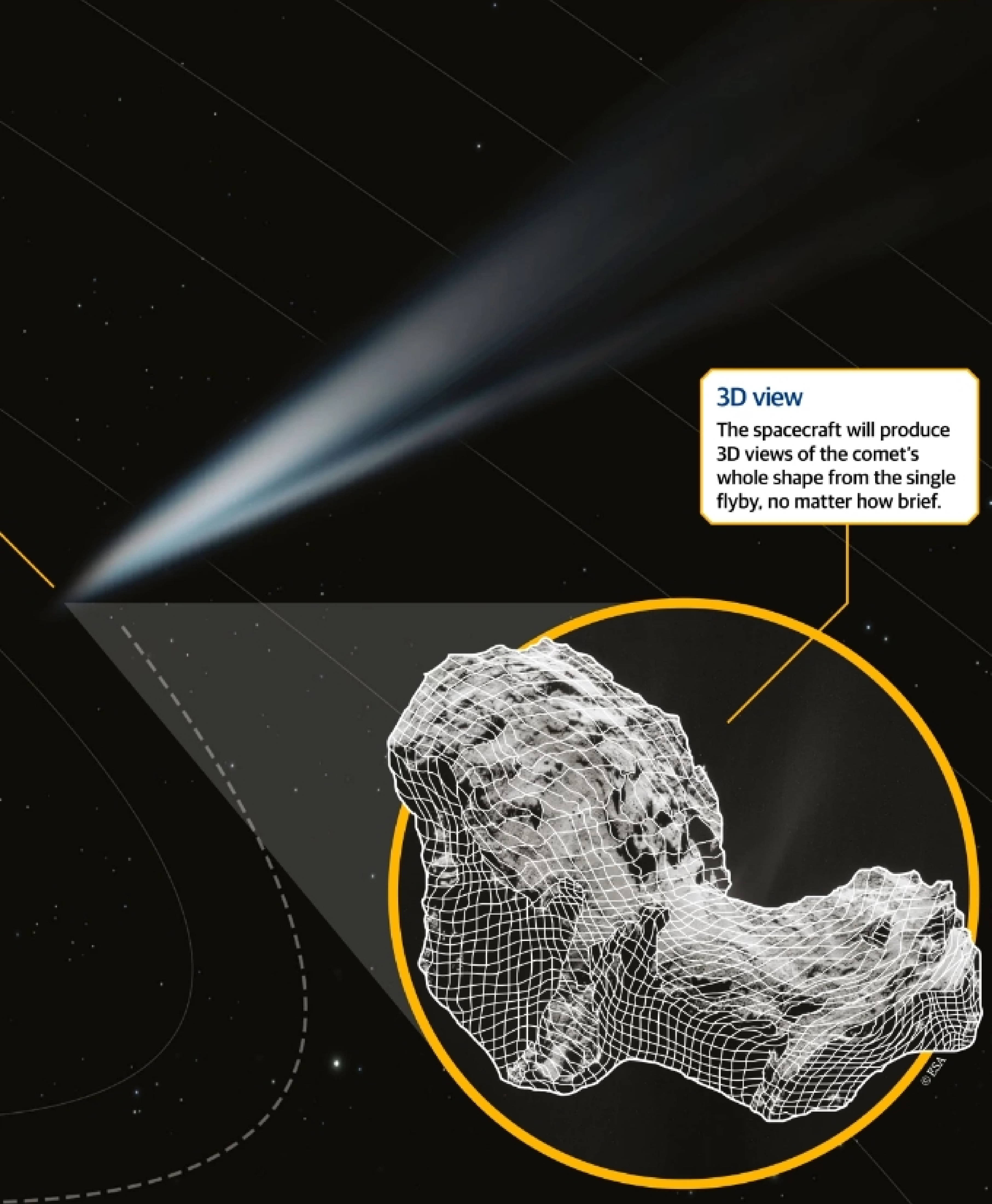
The spacecraft will include instruments that will measure solar wind and plasma near and around the comet.

Three-in-one

The mission will comprise three spacecraft – one mothership to fly far from the comet, and two smaller spacecraft to fly closer.

3D view

The spacecraft will produce 3D views of the comet's whole shape from the single flyby, no matter how brief.



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Comet Interceptor by the numbers

€150 MILLION

Total cost of the mission in euros

2028

Proposed launch date for the mission

0.8 to 1.2

Distance in AU to the Sun the comet needs to approach to be reached by the mission

1,000km

Closest approach of the main spacecraft to the comet

70km/sec

Maximum likely flyby speed for the spacecraft at its target

10km/sec

Minimum likely flyby speed for the encounter

2033

Time by which the mission must be completed due to costs

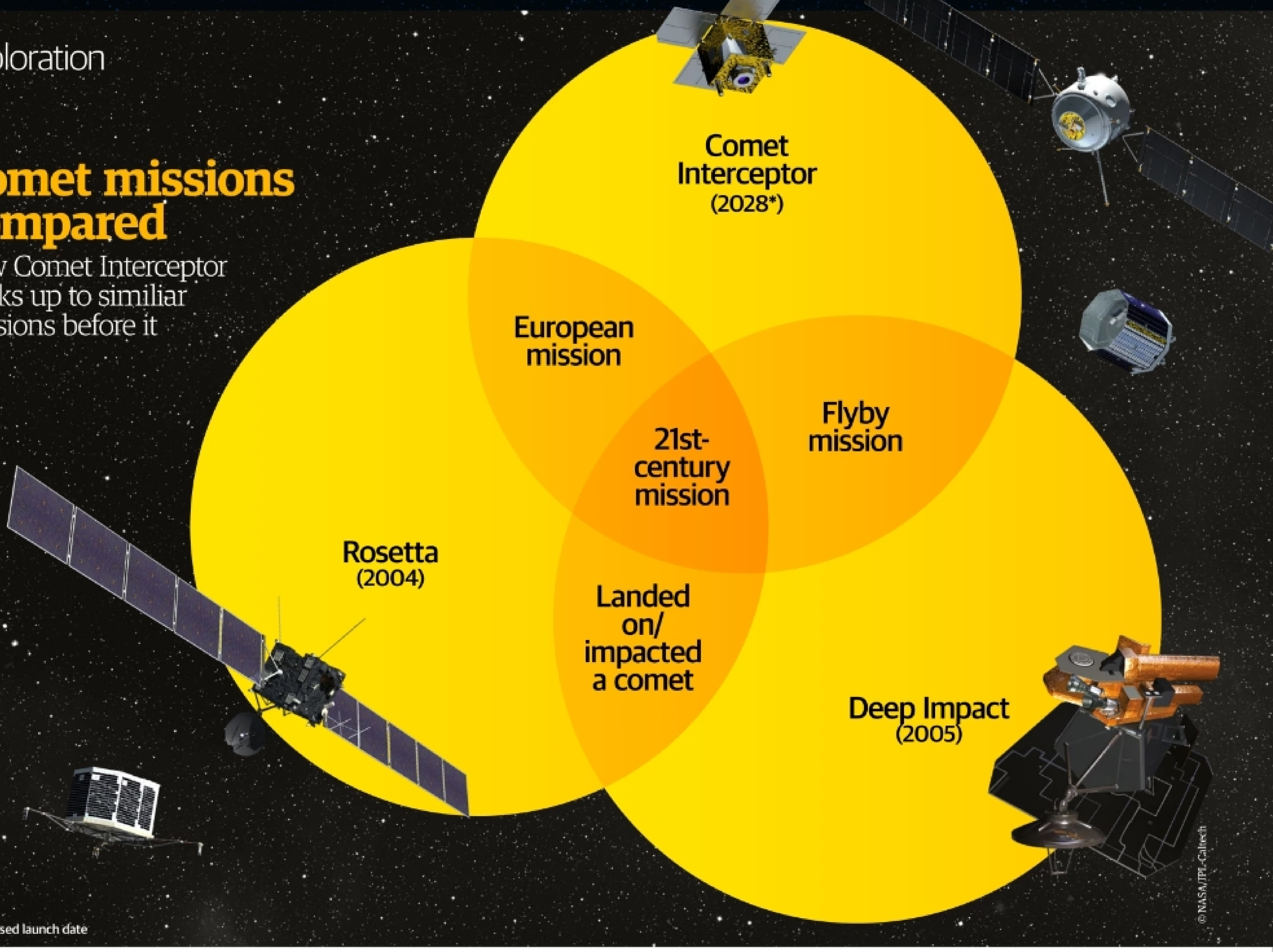
1

Number of interstellar objects found in our Solar System so far

© Illustration by Adrian Mann

Comet missions compared

How Comet Interceptor stacks up to similiar missions before it



*Proposed launch date

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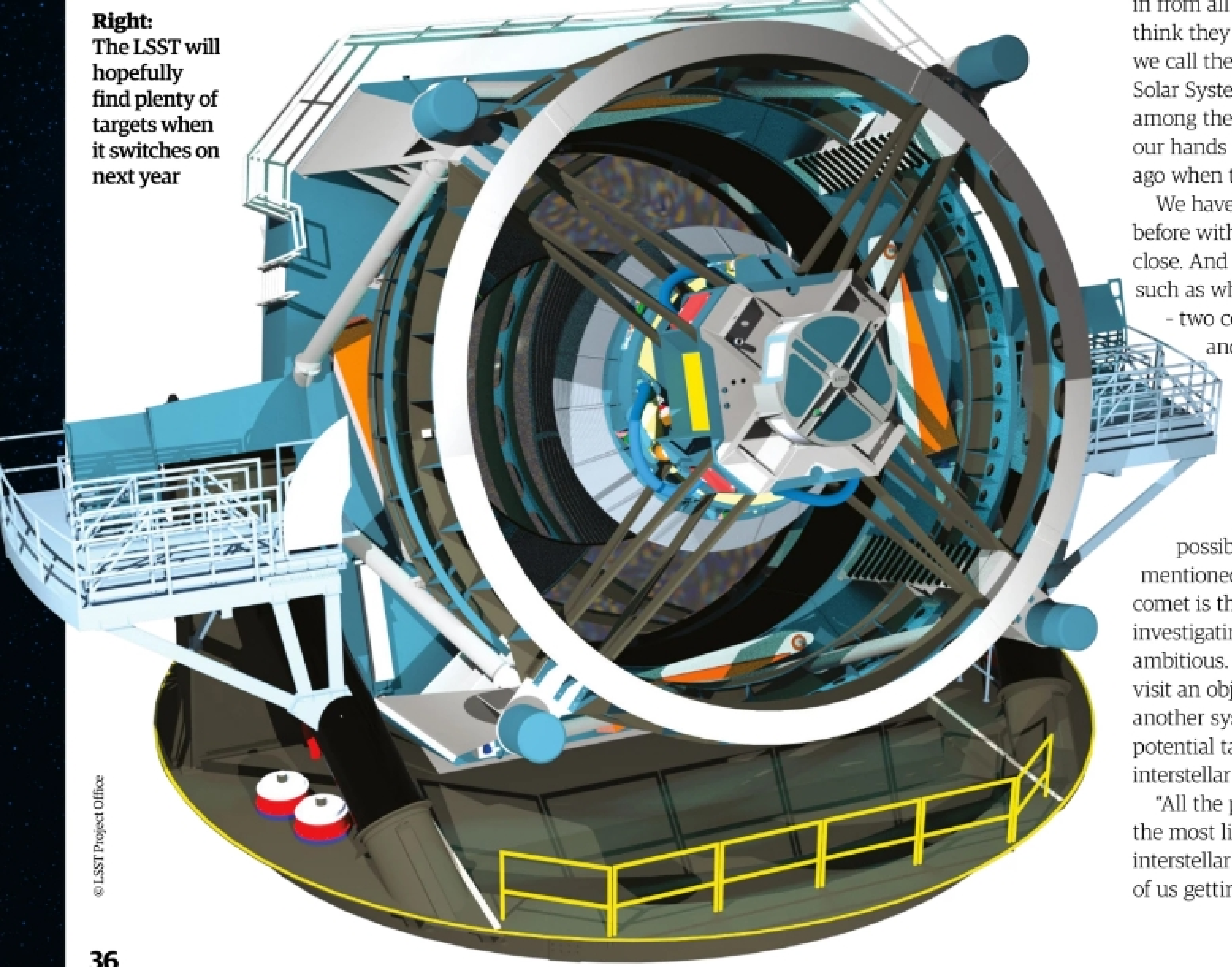
Right: The LSST will hopefully find plenty of targets when it switches on next year



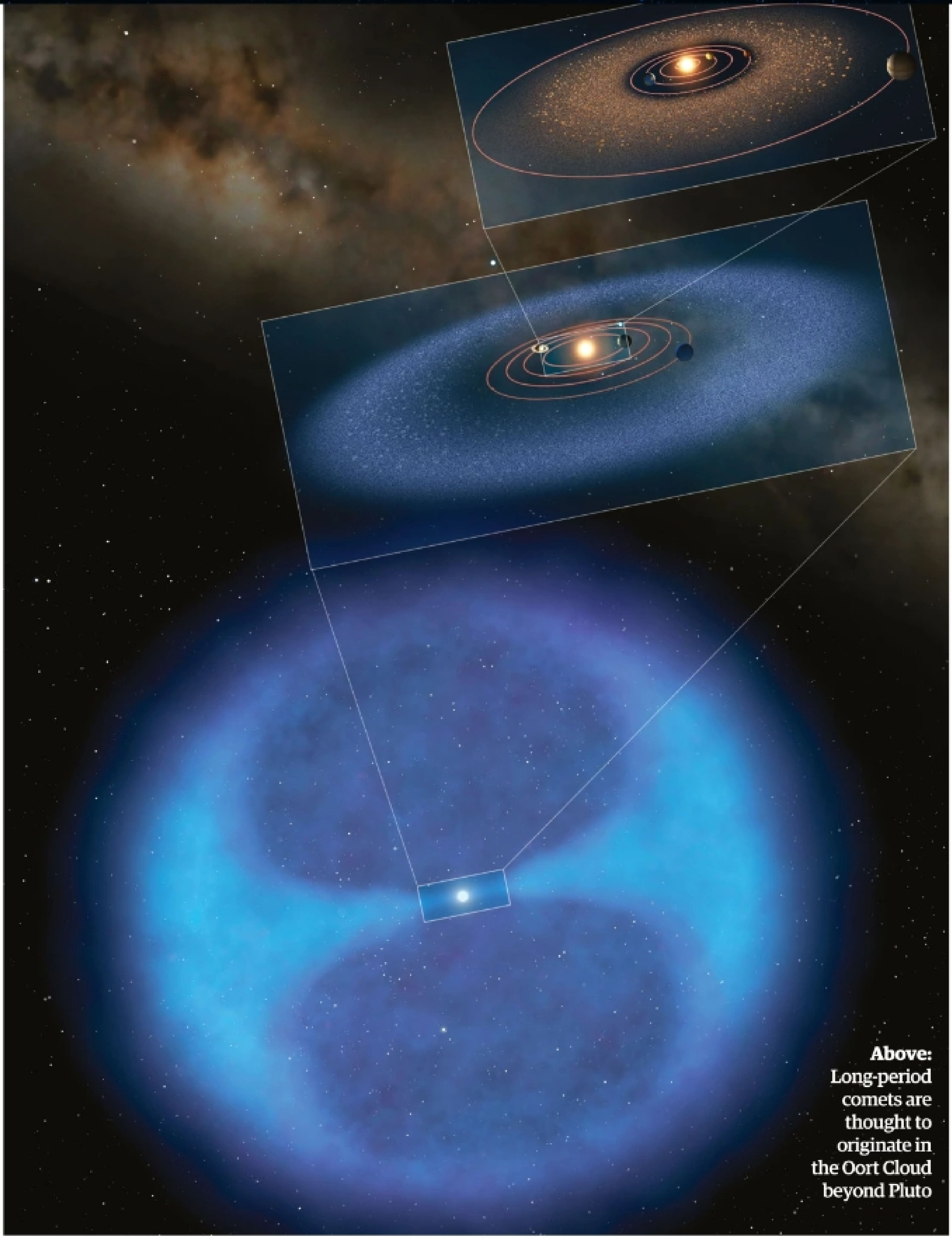
© LSST Project Office

in from all sorts of weird and wonderful angles. We think they come from this hypothetical area that we call the Oort Cloud, way out on the edge of the Solar System beyond Pluto. And these are probably among the most pristine material that we can get our hands on, stuff that was there 4.5 billion years ago when the Solar System formed."

We have been able to study long-period comets before with telescopes, but we've never seen one up close. And there are a lot of unanswered questions, such as whether they are mostly binary objects - two comets stuck together, like Comet 67P - and what their surfaces look like. Surveys like the LSST are expected to find thousands of comets every year, and some of these will be hoped to be long-period comets that Comet Interceptor could visit.

But there is another incredibly alluring possibility with this mission that we haven't mentioned yet. Because while a long-period comet is the main target, the team will also be investigating the possibility of something far more ambitious. They will see if it might be possible to visit an object not from our Solar System, but from another system entirely. Comet Interceptor's other potential target is not a long-period comet, but an interstellar object from afar.

"All the planning is for a comet, because that's the most likely case," Snodgrass explains. "The interstellar object is a possibility, but the chances of us getting one are pretty slim. With the comet



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Above: Long-period comets are thought to originate in the Oort Cloud beyond Pluto

> "It would be really amazing to get a feel for other types of materials that we find out there in the universe" **Dr Ashley King**

we'll have a few years warning - we'll see it coming. Whereas if [an interstellar object] behaved like an asteroid and it doesn't have activity, you wouldn't see it until it's really close to you. Then we won't have a lot of warning, and the chances we can intercept it are slim. If we did find one with enough time, I think there would be a very strong push to do so because scientifically that would be an amazing opportunity."

That might sound far-fetched, but it's very possible. In October 2017 we detected an interstellar object inside our Solar System for the first time. Dubbed 'Oumuamua, it's thought this object - which may have been either an asteroid or a comet - had been ejected by a star from another planetary system and had made the long trek across interstellar space to our own Solar System. It visited only briefly, however, and is now too far for us to visit. But it came close to our Sun long enough for us to study it with telescopes.

It's hoped that at any given moment there might be at least one interstellar object in our Solar System. Finding them is difficult because they can be incredibly dim and move very quickly. But if one can be found while Comet Interceptor is waiting at L2, then the mission may not go to a long-period comet at all. It may instead attempt to intercept an interstellar comet, also a historical first and, arguably, a greater cause.

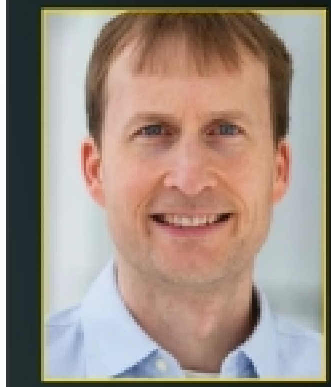
"It probably has to be [the most alluring possibility]," said Dr Nicholas Attree, a research fellow and comet expert from the University of Stirling in Scotland. "If you had a chance to go for an interstellar object it would be really amazing and

What's going to be the biggest breakthrough?

Members of the Comet Interceptor team discuss their biggest hopes for the mission

"It will be like getting to look at a time capsule"

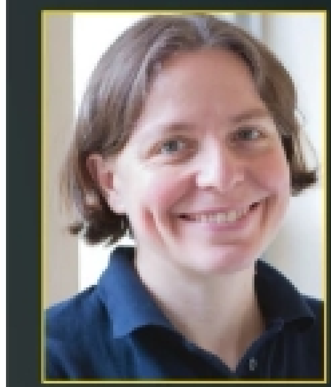
Matthew Knight, University of Maryland and Consortium Member



"To me, the most important aspect of the mission will be getting detailed observations of a 'new' comet nucleus for the first time. All comets humanity has visited have been in the inner Solar System for many years, but Comet Interceptor will give the first glimpse of what a comet looks like before it has been extensively heated by the Sun. It will be like getting to look at a time capsule from our Solar System's distant past."

"It consists of three spacecraft, a first among cometary missions"

Marina Galand, Imperial College of Physics, lead on the magnetometer instrument on spacecraft B2



"One exciting originality of Comet Interceptor is that it consists of three spacecraft, a first among cometary missions. This enables multipoint measurements, which are essential to build a 3D picture of the gas, dusty plasma and magnetic field environment around an active cometary nucleus. This will revolutionise our view of the interaction of a comet with the space environment it encounters and offer critically new insights on how energy, momentum and mass are transferred between the comet and its environment."

completely unprecedented. In some small way I'd be kind of sad that we didn't go to a comet, but it would be a unique opportunity to do that."

King agrees that while it would be a tough decision, the possibility of visiting an interstellar object would be too tempting to pass up. "I think I would take an interstellar object," he said. "It would be really amazing to get a feel for other types of materials that we find out there in the universe, and see how those materials compare to other stuff in our own Solar System. It would be a new venture."

Finding such a target will be no easy feat. The team will be forced to make a tricky decision while waiting at L2 – should they go for the first target they see, or wait for the possibility of an even better object in the future? That will be decided in discussions to take place over the next few years, after the design of the mission has been refined.

The spacecraft will have funding to remain at L2 for three years. If in that time the team does not find a suitable target, either a long-period comet or an interstellar object, then they do have back-up objects to visit, such as a short-period comet called 73P/Schwassmann-Wachmann 3. While this would be less interesting, it is thought to be a comet that has broken apart, possibly revealing its core. So studying it, while slightly disappointing, would still provide a fascinating opportunity for unprecedented science.

Whatever happens, Comet Interceptor is set to be a mission like no other. It is the first time a space mission will have been launched with no specific target in mind, and it will explore an object never seen before too. Before the spacecraft even launches, however, surveys like the LSST are expected to throw up some potential targets, possibly even including some interstellar objects. It could even be that an optimal target is selected before Comet Interceptor launches. If not, it will wait patiently before heading out for its brief but historic encounter with an unseen world.

"We've done lots of simulations, and we're pretty confident that we will have targets we can reach," says Snodgrass. "If we find out they're plentiful, we can wait for a really good one. Whereas if these things only come along once every few years, then we'll go for the first one that we can."

©ESO

Above: Objects from other stars may regularly approach our Sun – we just need to find them

Right: The mission could explore an interstellar object like 'Oumuamua for the first time

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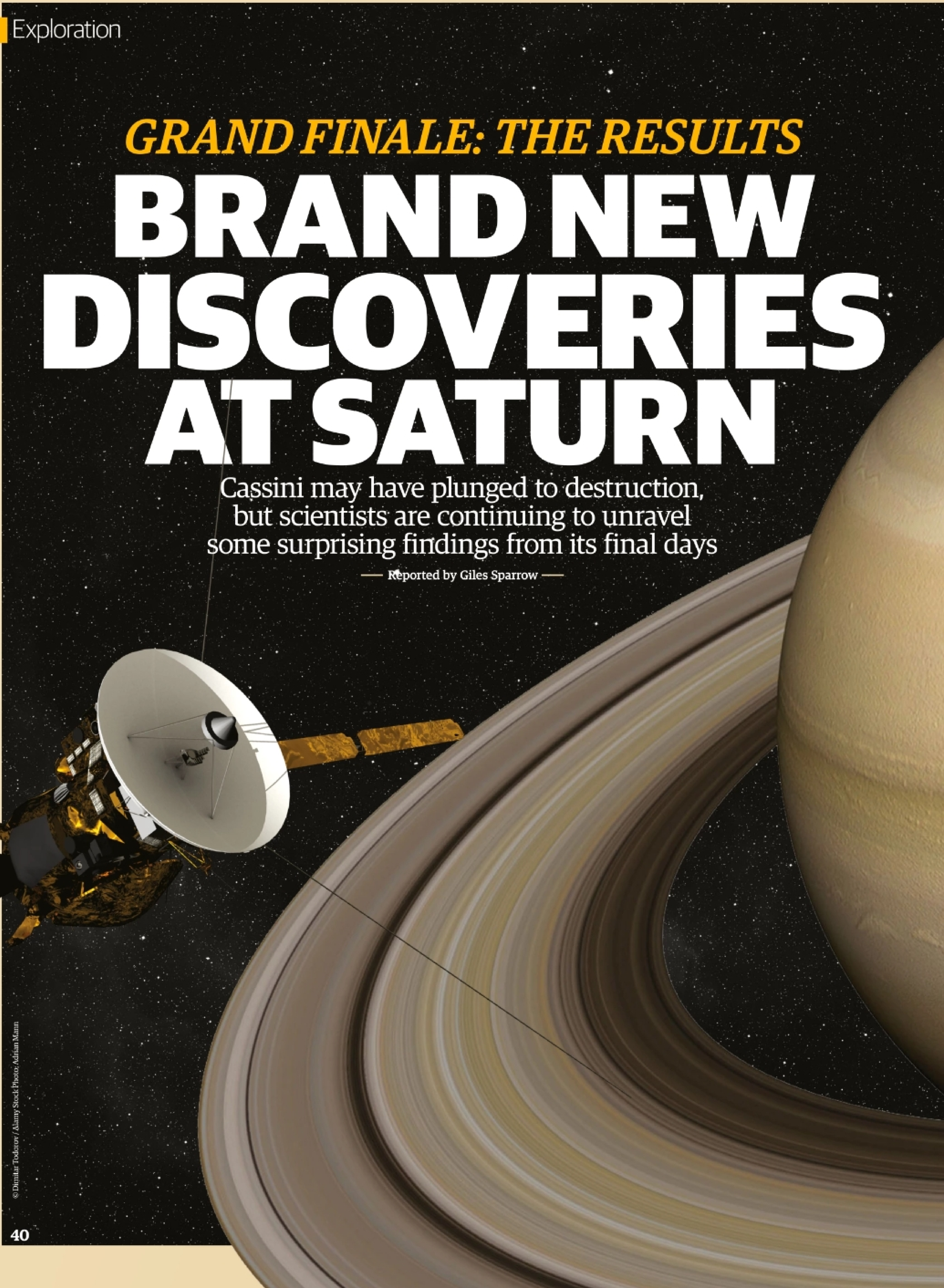
GRAND FINALE: THE RESULTS

BRAND NEW DISCOVERIES AT SATURN

Cassini may have plunged to destruction, but scientists are continuing to unravel some surprising findings from its final days

— Reported by Giles Sparrow —



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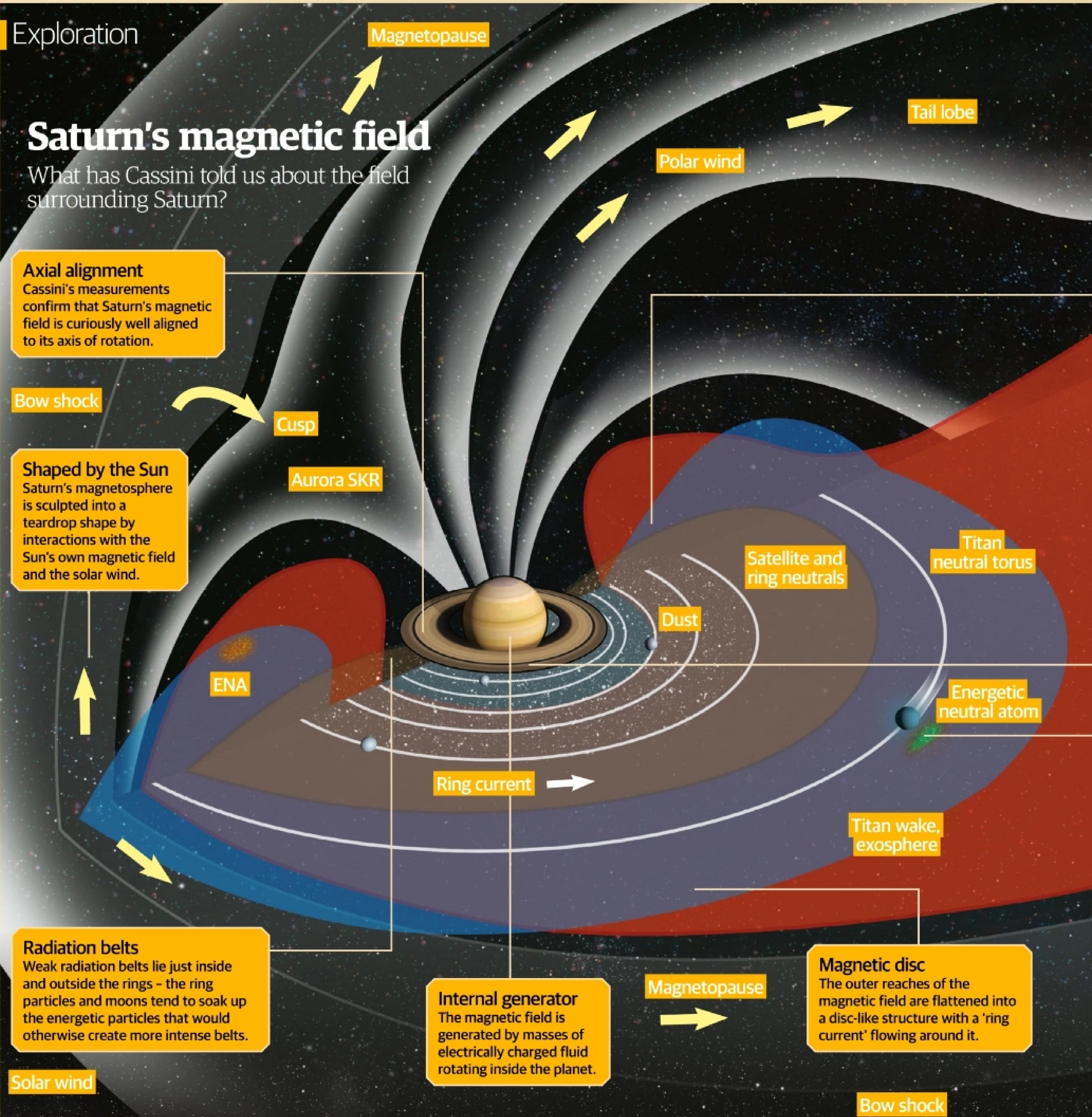
In more than 13 years orbiting the beautiful ringed planet the Cassini space probe transformed our understanding of both Saturn and its moons. When it disappeared for the last time into the gas giant's upper atmosphere in September 2017 it marked the end of a remarkable and hugely successful mission.

But while Cassini is gone, it's certainly not forgotten; mission scientists are still sifting through the wealth of data it sent back, particularly during the ten-month 'Grand Finale' – a series of daredevil loops that sent the probe between the planet's upper atmosphere and its innermost rings, providing a unique look at the environment close to Saturn. And, after months of analysis, they've now begun to reveal some of the stunning and unexpected discoveries from Cassini's final year.

Saturn's magnetic field

What has Cassini told us about the field surrounding Saturn?



Axial alignment
Cassini's measurements confirm that Saturn's magnetic field is curiously well aligned to its axis of rotation.

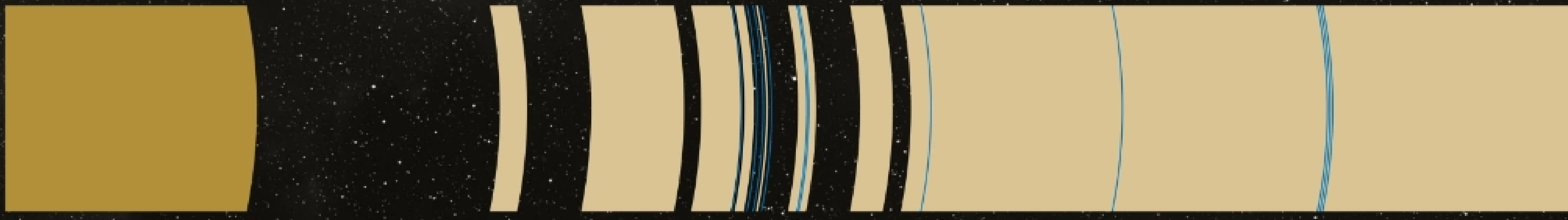
Shaped by the Sun
Saturn's magnetosphere is sculpted into a teardrop shape by interactions with the Sun's own magnetic field and the solar wind.

Radiation belts
Weak radiation belts lie just inside and outside the rings – the ring particles and moons tend to soak up the energetic particles that would otherwise create more intense belts.

Internal generator
The magnetic field is generated by masses of electrically charged fluid rotating inside the planet.

Magnetic disc
The outer reaches of the magnetic field are flattened into a disc-like structure with a 'ring current' flowing around it.

How Saturn's rings were made



Idea 1: Shattered moonlets

One theory is that the rings formed when comet impacts broke up one or more small moonlets orbiting inside Saturn's Roche limit.

Idea 2: Lunar break-up

Alternatively, a larger moon may have been pushed inside the Roche limit where tidal forces eventually tore it apart.

Varied rings

Over a long period, collisions and tidal forces spread the debris evenly around the planet and began to draw smaller particles closer to the planet.

Tidal gaps

Gaps in the rings developed where orbiting particles would experience regular tidal pulls from more distant orbiting moons.

© NASA/JPL-Caltech; Nicholas Forder; Tobias Roetsch

Plasma cavity
The magnetosphere is filled with a plasma containing electrically charged particles from a variety of sources – mostly water vapour from Enceladus.

Puzzling rotation
Because the magnetosphere is aligned with Saturn's polar axis it can't be used to measure the planet's rotation. As a result, even after Cassini we still don't know how fast Saturn's interior spins!

Shielding Titan
Saturn's giant moon has no intrinsic magnetism of its own, but its atmosphere is protected by an induced magnetic field as it moves through Saturn's magnetosphere.

Comet enrichment
Studies of ring rain particles suggest that the relatively pure ice has been enriched with more complex chemicals, perhaps from comet ices.

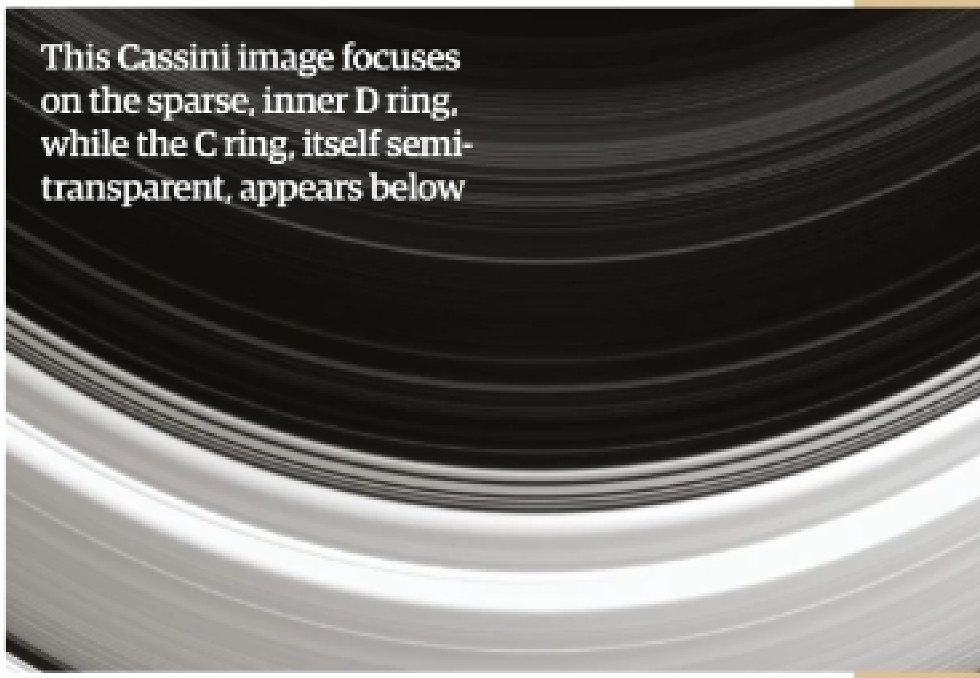
Cassini's Grand Finale was carefully planned from the outset. "The spacecraft had already gone way beyond its expected lifetime and through two extended missions, but it was running out of fuel, and we couldn't just leave it to wander through the Saturn system," explains Dr Hunter Waite of the Southwest Research Institute in San Antonio, Texas. "The risk of contaminating Titan or Enceladus if the spacecraft hit them was too large to ignore. We had to come up with a deterministic way to destroy the spacecraft, so we used Titan's gravity to steer Cassini in between the rings on an elliptical path."

Cassini's orbit had been carefully managed to reduce the risk of a catastrophic encounter with one of the countless ring particles in orbit around Saturn. With the rings confined to a narrow plane above Saturn's equator the spacecraft's orbit was sharply tilted or inclined, ensuring that it would cross the dangerous ring plane only briefly.

"Travelling at speeds of up to 37 kilometres per second [23 miles per second] relative to the planet, even a BB-sized object [a small pellet] can take out a spacecraft," says Waite, "so, just like everything we did, it was carefully orchestrated and verified using all the data we had to confirm the region we were sending the spacecraft through was dust-free enough that it wouldn't cause us a problem and potentially destroy the spacecraft prematurely. Fortunately that proved right: we orbited 22 times and then after we bumped it slightly with another close approach to Titan, Cassini was gone. When it got into the upper atmosphere it didn't take long to just tumble and burn up."

Hunter Waite is principal investigator for one of Cassini's key science tools, the Ion and Neutral Mass Spectrometer (INMS), and the data his instrument collected during its final months of operation is already changing ideas about the structure and evolution of Saturn's rings.

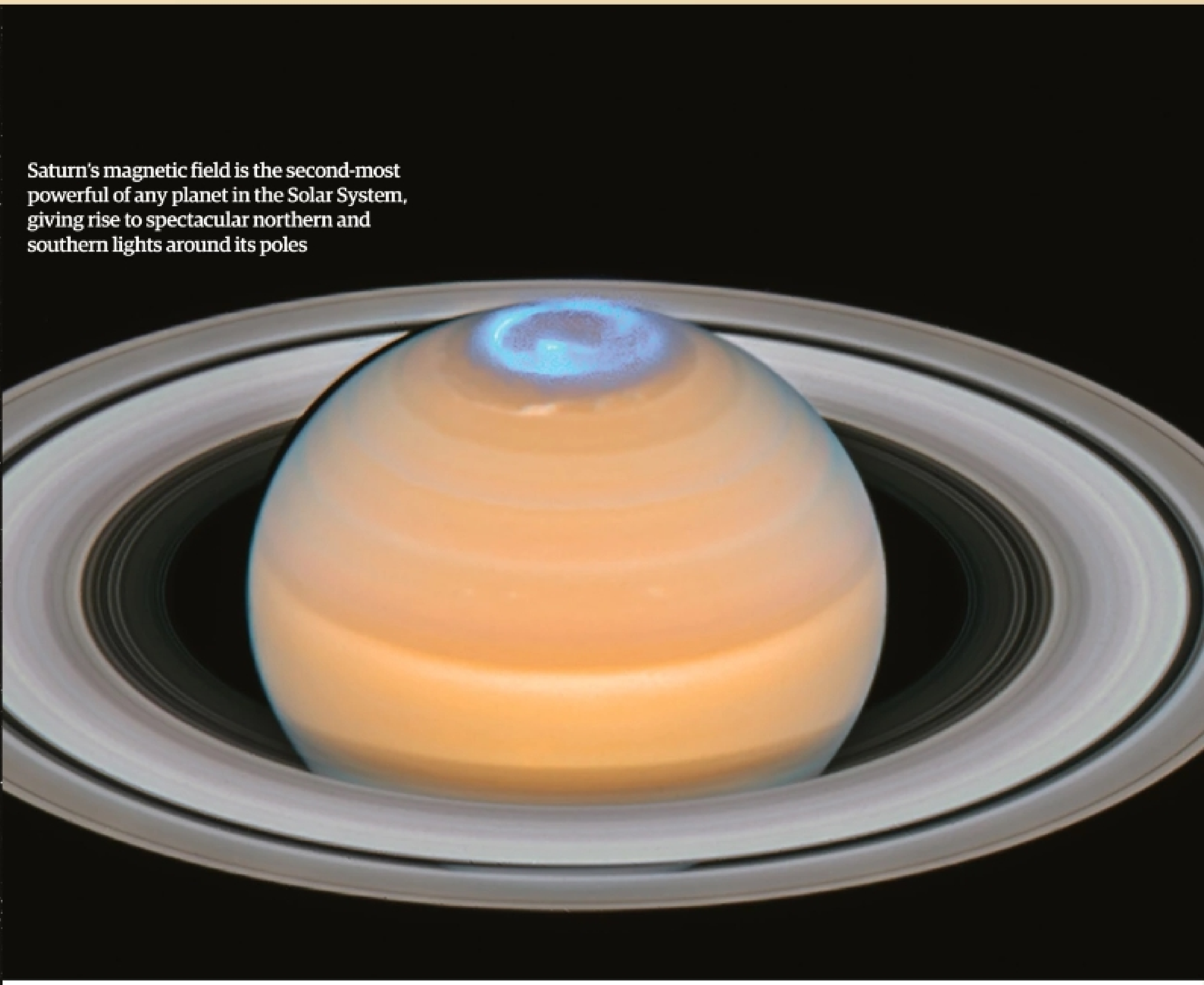
"The mass spectrometer is the spacecraft's sensitive nose," he explains. "It can determine the composition of gases with high sensitivity – we used it to identify all the gases and ionised material [electrically charged particles] around Titan and coming out of the famous plumes on Enceladus, but especially as we flew between the rings and upper atmosphere during the Grand Finale."


This Cassini image focuses on the sparse, inner D ring, while the C ring, itself semi-transparent, appears below

The INMS, like any mass spectrometer, analyses the mass of individual gas molecules through the way they are deflected inside an electromagnetic field, but Cassini's high speed also extends its range beyond naturally gassy materials: "If we encounter a dust or ice grain at about 15 kilometres per second [9.3 miles per second] hitting our instrument antechamber, it can break apart and we'll see the volatile residue from that as well. We used that information about grains to analyse the plumes over Enceladus, and also during the Grand Finale."

For Waite and his colleagues, the most intriguing questions surrounded the composition of trace gases tenuously held in Saturn's outermost atmosphere – the exosphere – and the nature of the so-called 'ring rain' – material that slowly sifts down from the innermost D ring into the atmosphere around the equator. The existence of a 'rain' of fine water-ice particles was proposed in the early 1980s to explain certain features of Saturn's electrically charged ionosphere, and the infalling material has since been seen to leave visible traces in Saturn's

Saturn's rings are formed of ice, dust and rocks



Saturn's magnetic field is the second-most powerful of any planet in the Solar System, giving rise to spectacular northern and southern lights around its poles

> "Cassini was gone. When it got into the upper atmosphere it didn't take long to just tumble and burn up" **Dr Hunter Waite**

clouds, but Cassini's Grand Finale was the first chance to study this material in detail.

"When we saw the first spectra, at the lowest altitudes in particular, we were just startled," recalls Waite. "We'd expected to see the signatures of hydrogen and helium, and maybe a bit of water if we were lucky. But there was also methane, molecular nitrogen, carbon monoxide, carbon dioxide... There was water too, of course, but also ammonia, and all kinds of organic-compound fragments from something that broke apart in our instrument. And there was a lot of this material – if you assume it's going all the way around the planet in the equatorial region, it's something on the order of 10,000 kilograms [22,046 pounds] of material falling into the atmosphere every second."

The unexpected presence of chemically complex material close to Saturn was reminiscent of material the spacecraft found near Titan, but Waite's colleagues were able to rule out that perhaps they were simply measuring particles trapped around Titan that had later dislodged at high speeds. "One nice thing was that we had another measurement to verify at least part of what we saw," he explains. "Don Mitchell [of Johns Hopkins University] and his colleagues on the Magnetospheric Imaging Instrument used a completely independent technique to detect nanometre-scale grains of material crashing into their instrument."

Cassini's spectrometer, however, detected a mix of gases and grains. Gases including hydrogen, helium, methane, molecular nitrogen and carbon monoxide were detected alongside volatile compounds such as water, ammonia and chemically complex carbon-based 'organic' molecules released as the nanograins broke apart on impact. And since INMS sampled material it encountered along Cassini's flightpath at various locations, it can offer some direct insight into the likely origins of the different molecules. "The only material that probably originates in the atmosphere was lightweight hydrogen and helium," comments Waite. "The other material all seems to be coming from the ring system and falling into the atmosphere."

Models show that the 'rain' originates from the continuous grinding down and inward drift of material from the inner rings, so the new data suggests the ring particles themselves are either more chemically complex than the blend of simple ices previously assumed, or that they have been significantly enriched by material from comets and other chemically complex icy objects in the outer Solar System.

The large amount of material in the ring rain is also revealing, as Waite explains. "At the present rate of infall, the D ring would disappear completely in 10,000 years or so, so there has to be a process to refresh it over time. It's quite intriguing and I know

Saturn
by the numbers

10,000kg
Mass of material falling onto Saturn as 'ring rain' every second.

22
Saturn radii
Saturn to the magnetopause, where its magnetic field is enveloped by the solar wind.

100kg per second
The rate at which electrically charged water ions from Enceladus are added to Saturn's magnetic plasma.

67-97°C
Temperature of gas in Saturn's tenuous outer atmosphere where the ring rain falls.

126,000 kilometres per hour
Cassini's top speed as it sped above Saturn during its Grand Finale orbits.

2,400 kilometres
Width of the gap between Saturn's upper atmosphere and the inner edge of the D ring.

294
Total number of orbits made by Cassini around Saturn.

Surprises at Saturn

Cassini found out much about the ringed planet, but experts weren't expecting these

Cassini's final plunge

To ensure that Cassini didn't contaminate any of Saturn's moons, the mission ended its 13 years of service via a controlled entry into the gas giant's atmosphere. It's here that the spacecraft broke up as it plunged through the layers and layers of gas, succumbing to the planet's pressure.

Strangely flat magnetic field

Unlike the other outer planets in our Solar System that have tilted magnetic fields, Saturn's is perfectly straight and, according to our understanding of how these fields are made, this shouldn't be possible: according to the Cassini team it's the tilt that keeps the magnetic field from dying away. However, before the spacecraft plunged into the atmosphere it discovered that this wasn't the case – in fact, it could suggest that the ringed giant is generating its magnetic field in a different way, perhaps with many onion-like layers of flowing particles instead of a single zone.

Saturn's rings rain material

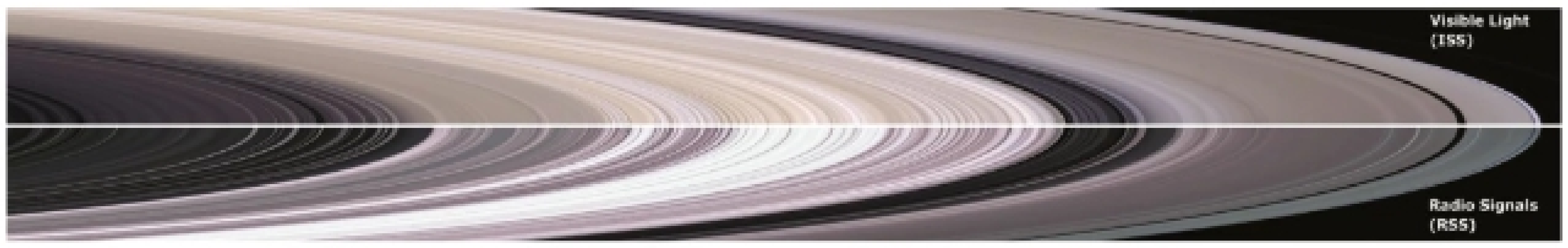
Saturn's innermost rings rain the equivalent of 1,800 cars per minute in tiny particles onto its atmosphere – unsurprisingly, it's called ring rain. Cassini uncovered that around Saturn's equator this rain deposits some 45,000 kilograms of ice, dust and gas every second, and it could mean that the rings are disappearing much more quickly than we initially thought. And, because the rain is made up of ammonia, nitrogen, methane and other such complex organic particles, it could be that the Saturn's top layers are being affected chemically.

More going on between its rings

It might look empty between its rings and its surface, but there's much more going on here than initially suspected – that's because of a connection between the upper atmosphere and the gas giant's crowning feature: streaming electric currents that flow between the rings and the outer atmosphere. However, it's not clear what's causing them or why they're there; that's something that the Cassini mission will help us to figure out. And that's not all – it's thought that there's also a belt of radiation that's coming from trapped energetic particles between the rings and the planet.

Cassini team members at NASA's Jet Propulsion Laboratory receive data from the first of Cassini's Grand Finale flybys

© NASA/ESA/Hubble; JPL-Caltech; Tobias Roetsch



This pair of images show Saturn's major rings in visible light (above) and in terms of their ability to block radio signals (below). Transparency to radio signals is a useful indication of how dense the material is

> “Most of us anticipate [the rings] will turn out to be considerably younger than Saturn” **Dr Hunter Waite**

there will be more work to come in this area on the lifetime of the rings. Most of us anticipate they'll turn out to be considerably younger than Saturn.”

Meanwhile, other instruments were also gathering important information about the environment close to Saturn. While imagers captured stunning close-ups of the planet's cloud features, the long antennae of the spacecraft's magnetometer detected patterns in the planet's powerful electromagnetic field. A team led by Professor Michele Dougherty of London's Imperial College, principal investigator for the Cassini Magnetometer, has announced two surprising discoveries – confirmation that the giant planet's magnetic field is aligned to its axis of rotation with eerie precision, and a strange new magnetic effect created in Saturn's upper atmosphere.

The magnetic alignment is particularly odd and hints at new phenomena still waiting to be discovered. Because magnetic fields are created by electrically charged material swirling in somewhat chaotic currents inside a planet, they are naturally misaligned – the fields of Earth and Jupiter, for example, are tilted at around ten degrees to their axis of rotation, while those of Uranus and Neptune are not just wildly tilted, but do not even pass through the centres of their respective planets. One possibility, Dougherty suggests, is that some outside effect is 'masking' the real alignment of the field and forcing it to align with its rotation axis.

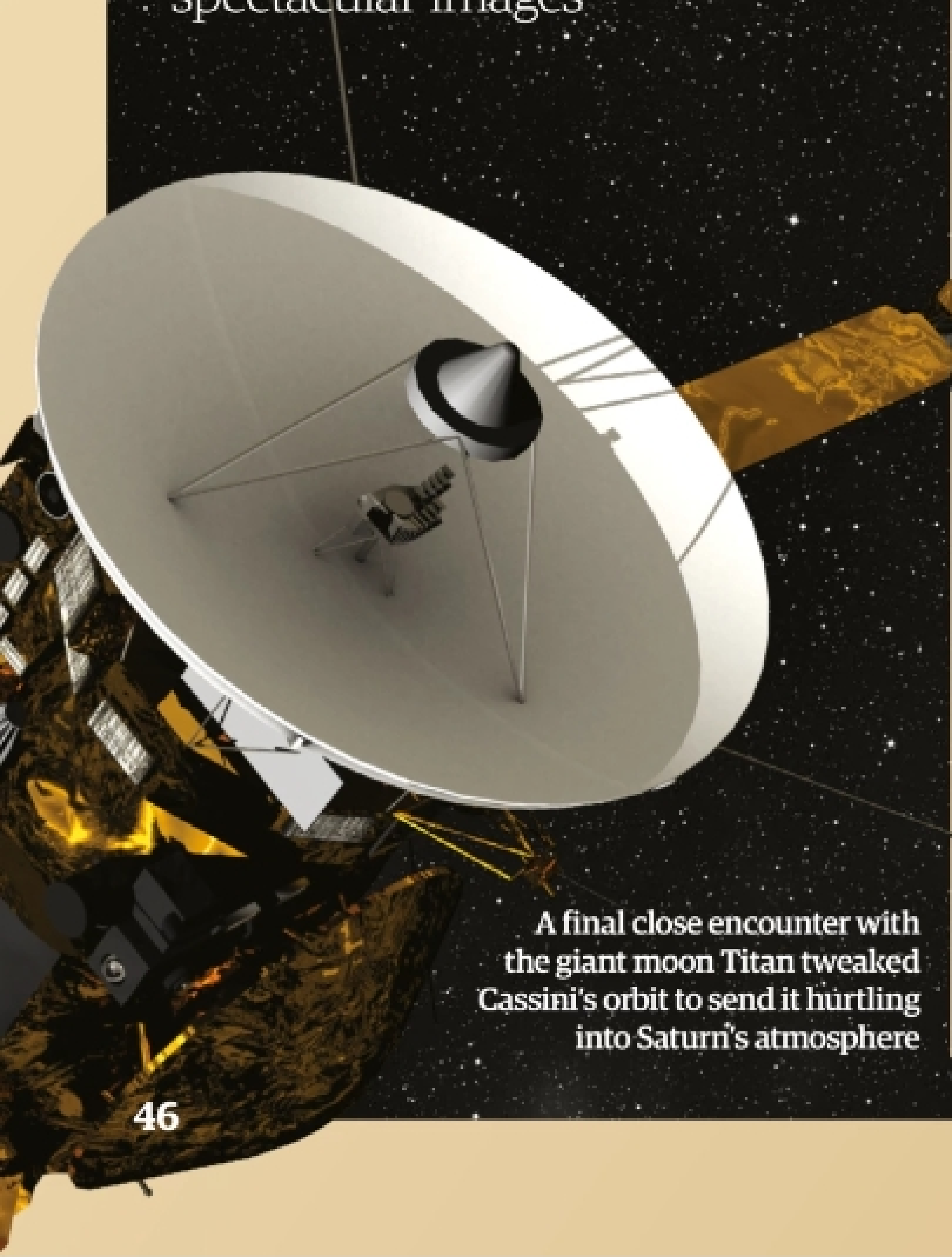
Perhaps the answer will turn out to be linked with another new magnetometer discovery – curious electric currents filling the space between Saturn and the rings. These seem to be generated as high-altitude winds flowing parallel to the equator cut through the magnetic field, but are still poorly understood. Waite hopes that the ring rain, which drifts through exactly the same region, may be able to shed some light: “We're trying to work with Michele to see if there are signatures in the material we measured and the atmospheric structure that correlate to those currents – that's an area we're actively researching right now.”

Many new insights clearly still wait in the data Cassini gathered in its final days, and we can clearly expect more exciting discoveries to come. But could something as tenuous as the misty rain drifting down from the rings onto Saturn change the way we understand the origin of the Solar System itself? Waite concludes by raising this intriguing possibility.

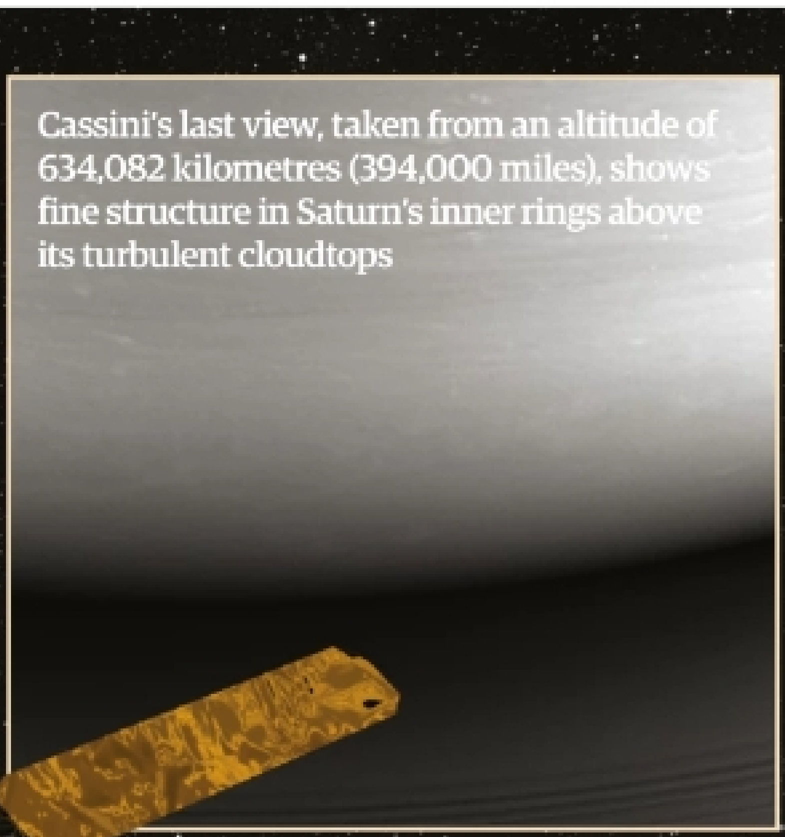
“If you dump that much methane onto the planet over the course of, say, 100 million years, you can give the upper atmosphere a veneer of carbon-bearing compounds that suggests an overall composition very different from that of the Sun,” he explains. Since observation-based estimates of each planet's composition are key to understanding how the raw materials of the Solar System were distributed and where the planets formed, the possibility that Saturn's internal constituents – and potentially those of other ringed planets – are hidden, rather than reflected by their outer layers could upset previous ideas. “It's certainly made me think about what appearances are saying versus what the ultimate reality might be for this whole process of Solar System formation and evolution.”

Cassini's final photography

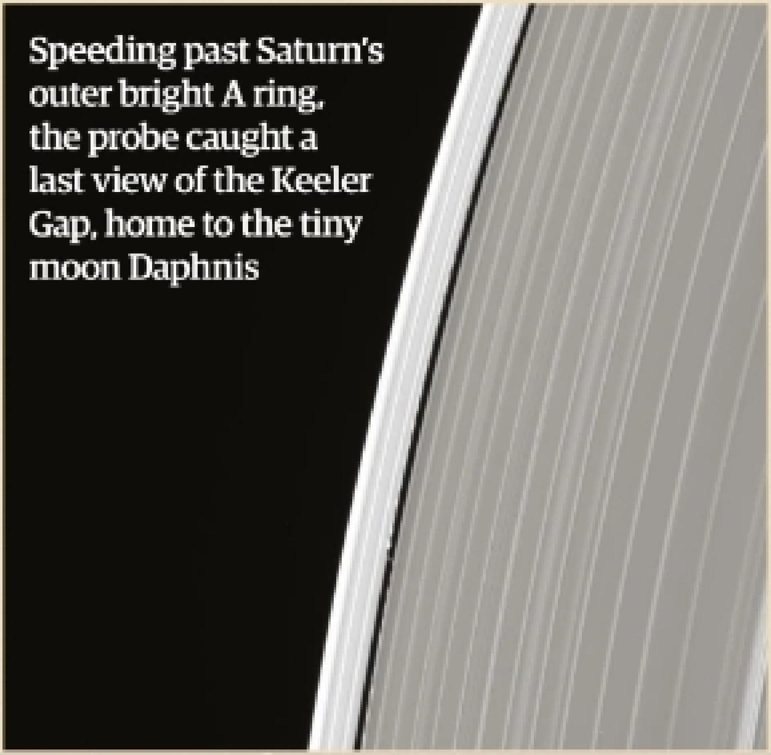
Its dive towards Saturn produced a series of spectacular images



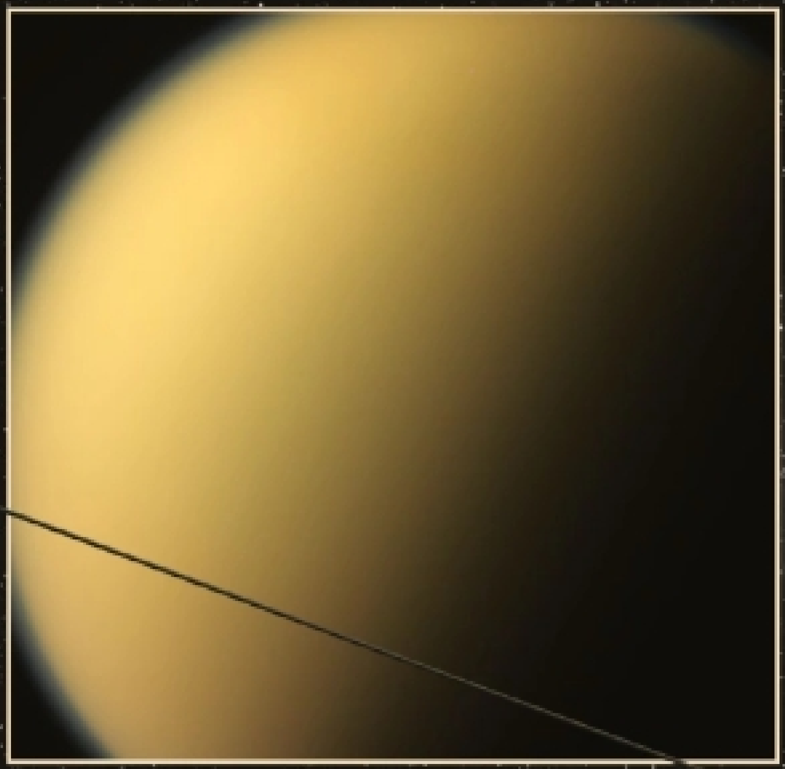
A final close encounter with the giant moon Titan tweaked Cassini's orbit to send it hurtling into Saturn's atmosphere

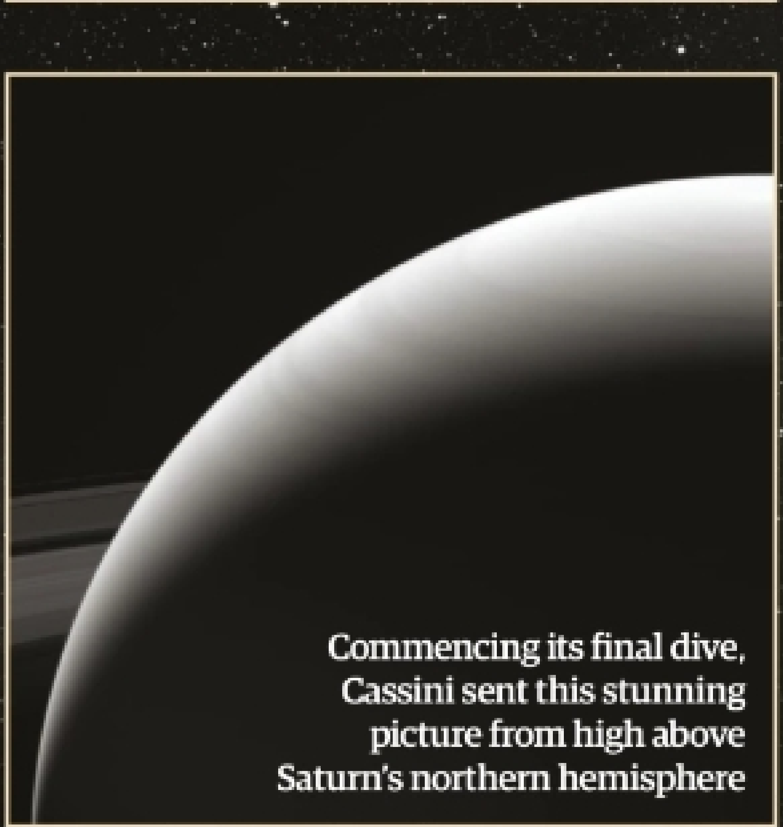


Cassini's last view, taken from an altitude of 634,082 kilometres (394,000 miles), shows fine structure in Saturn's inner rings above its turbulent cloudtops



Speeding past Saturn's outer bright A ring, the probe caught a last view of the Keeler Gap, home to the tiny moon Daphnis





Commencing its final dive, Cassini sent this stunning picture from high above Saturn's northern hemisphere

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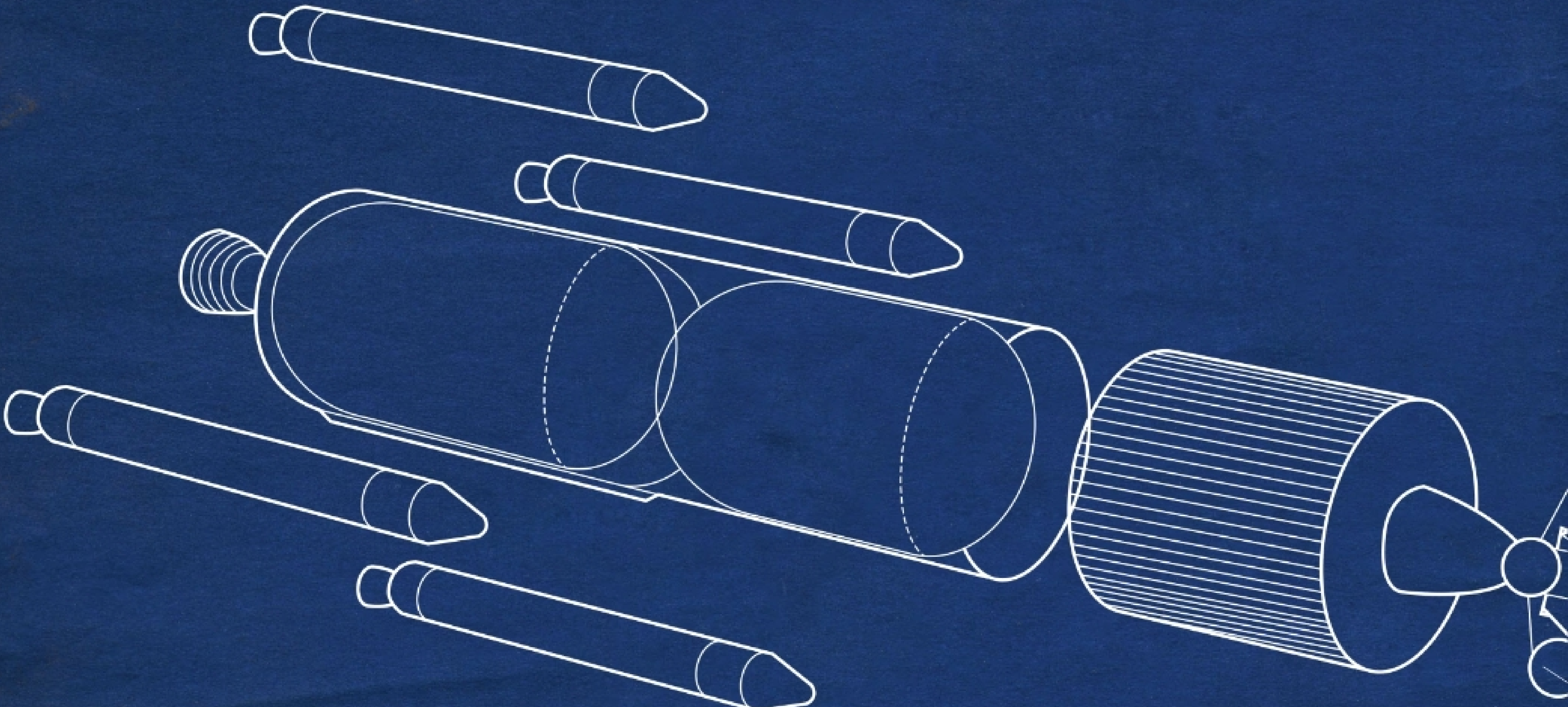
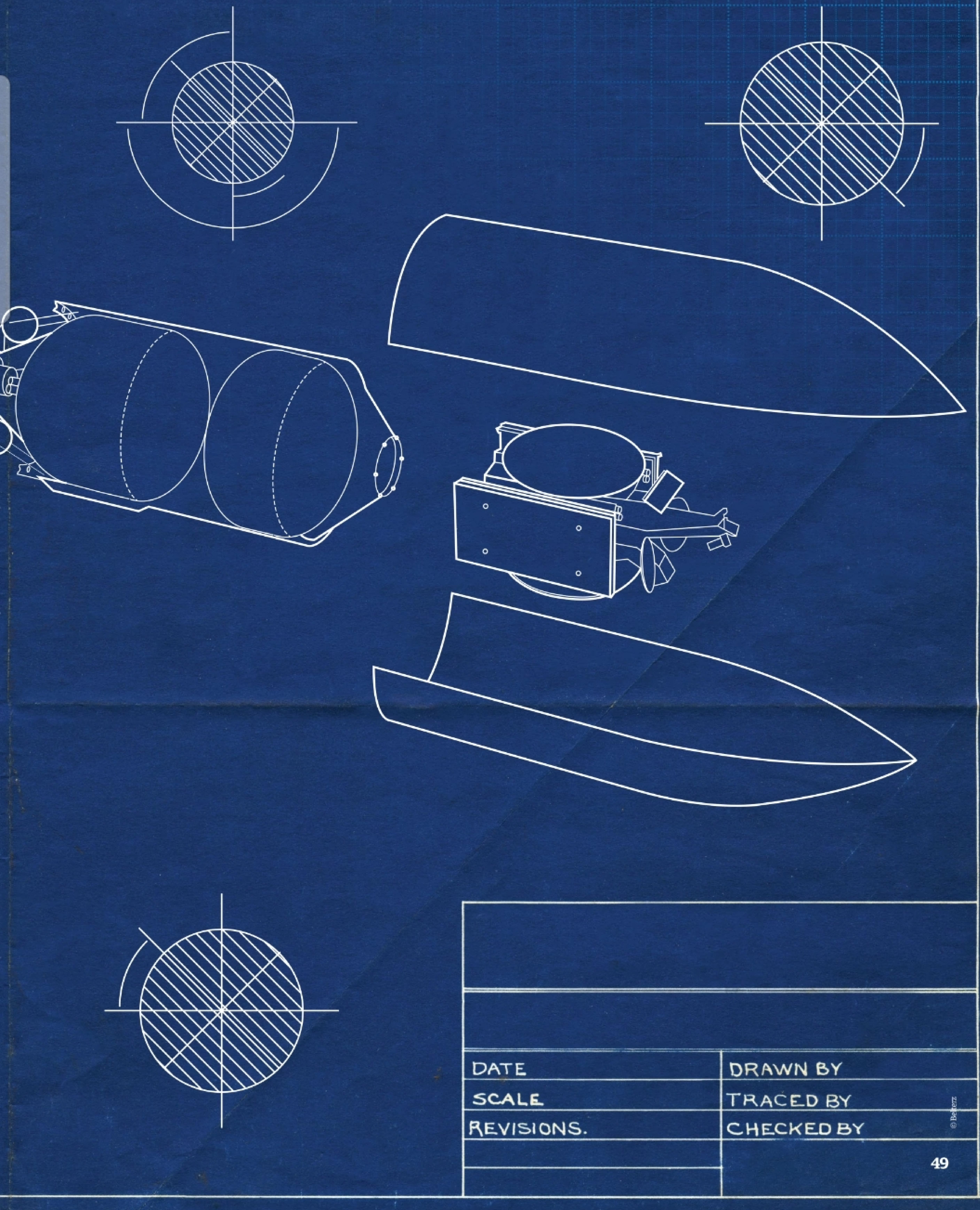


Bluffer's guide to ROCKET SCIENCE

Rockets of all kinds are still our only way of reaching space – but just how do they work?

Written by Giles Sparrow



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1

How rockets lift off

Rockets burn through most of their fuel in the first few minutes of their flight as they battle against Earth's gravity

Writers and inventors have dreamt of exploring the universe beyond Earth for centuries, but the real challenges of travelling into space only became clear in the 19th century. Experimental balloon flights showed that Earth's atmosphere thins out rapidly at high altitudes, and so even before powered flight became a reality, engineers knew that wings, propellers and other devices that create a forward or upward force by pushing against a surrounding medium like air would be no use in space. Another problem was that combustion engines – machines such as steam and petrol engines that generate power by burning fuel in the oxygen from Earth's atmosphere, a chemical reaction called combustion – would also fail in airless space.

Fortunately, a device that solved the problem of generating force without a surrounding medium had already been invented – the rocket. Initially used as weapons of war

1 Gravity

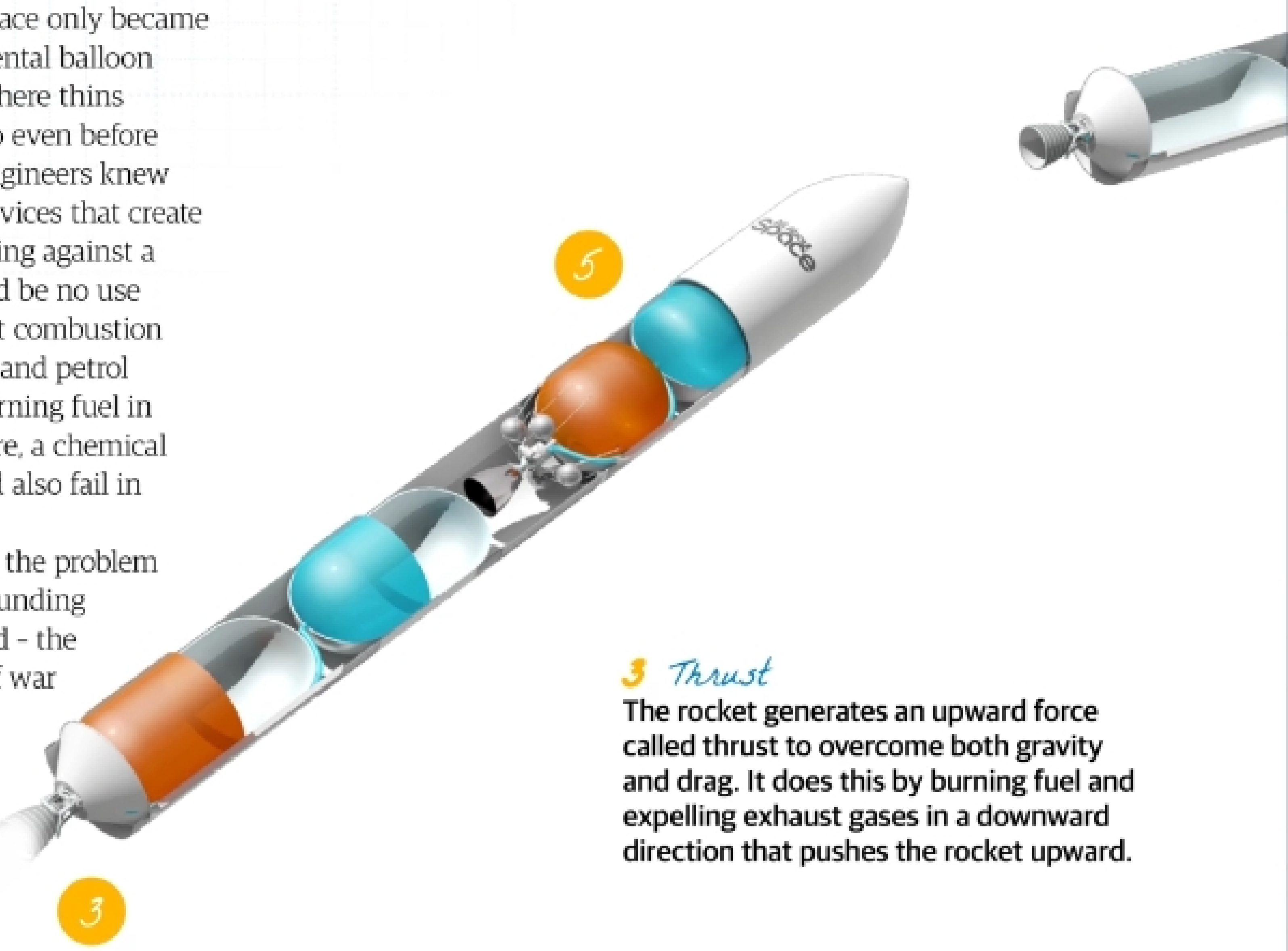
The force of gravity pulls everything towards the centre of the Earth, exerting a downward force of 9.8 newtons per kilogram on every part of the rocket.

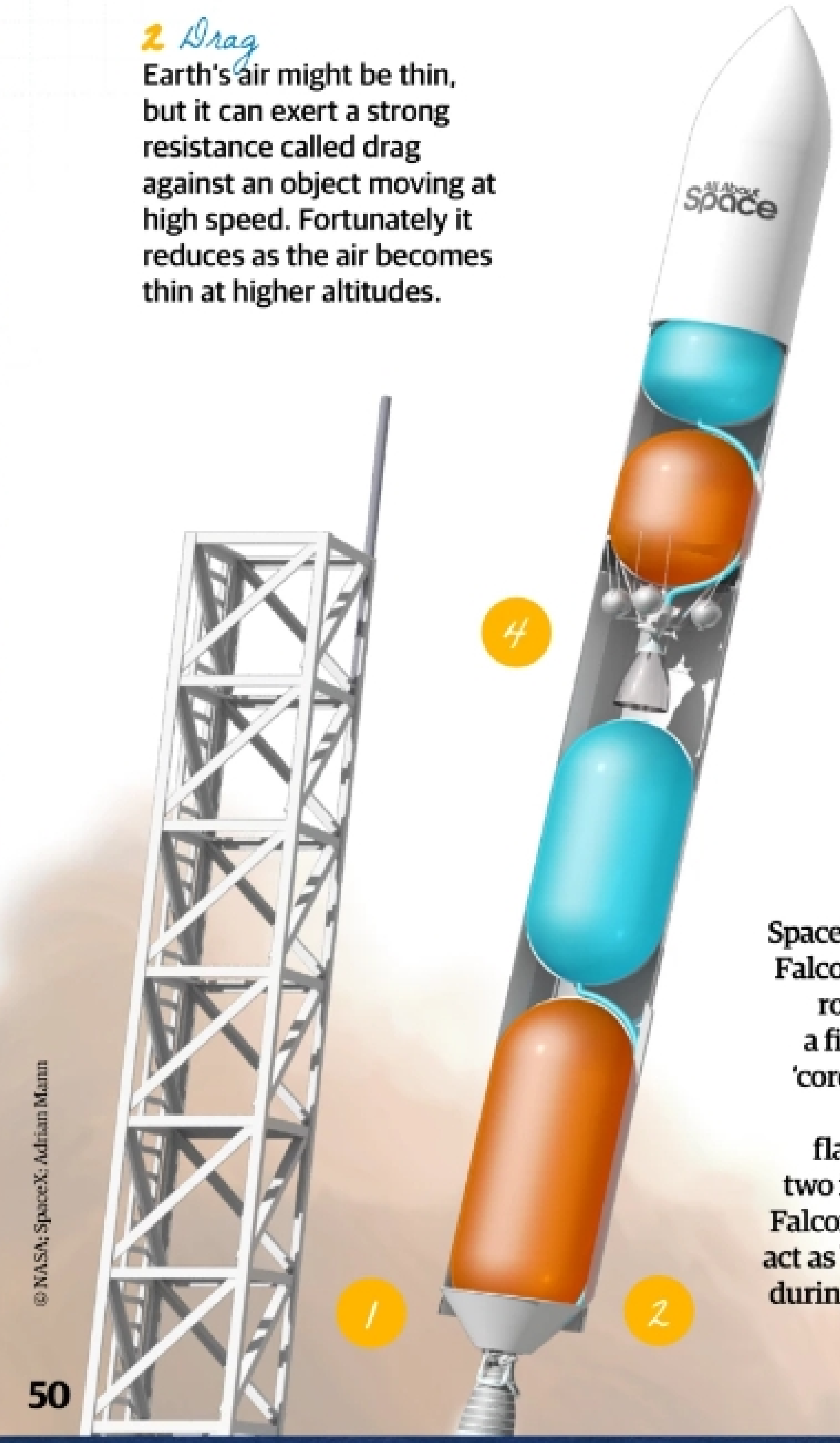
2 Drag

Earth's air might be thin, but it can exert a strong resistance called drag against an object moving at high speed. Fortunately it reduces as the air becomes thin at higher altitudes.

3 Thrust

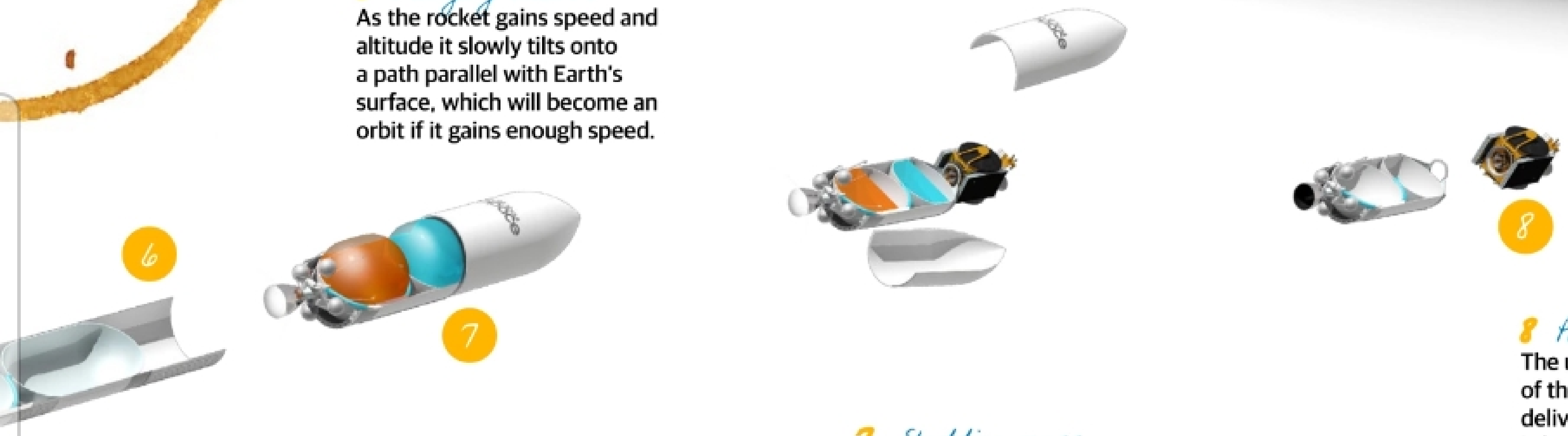
The rocket generates an upward force called thrust to overcome both gravity and drag. It does this by burning fuel and expelling exhaust gases in a downward direction that pushes the rocket upward.





Right: SpaceX's huge Falcon Heavy rocket has a first-stage 'core' Falcon 9 rocket flanked by two identical Falcon 9s that act as boosters during launch

© NASA; SpaceX; Adrian Mann



4 Slow start
At launch a rocket's weight is at its greatest. Even with the rockets producing maximum thrust they produce barely enough power to lift the rocket off the ground.

5 Rocket stages
Most rockets are designed with two or more stacked units called stages. The lowermost stage fires its engines until they are exhausted, then separates and falls away to reduce the overall mass being carried further towards space.

6 Changing altitude
As the rocket gains speed and altitude it slowly tilts onto a path parallel with Earth's surface, which will become an orbit if it gains enough speed.

7 Shedding mass
As the rocket continues to burn fuel its weight reduces, so although the thrust force from its engines remains constant, it has a greater accelerating effect.

8 Payload
The uppermost stage of the launch vehicle, delivered into orbit, is known as the payload. This may consist of a satellite or spacecraft, often with a separate rocket stage for further manoeuvres.

Left: The Space Shuttle's unique design channelled propellant from an external tank to the Shuttle's main engines during launch, while two large solid rocket boosters assisted

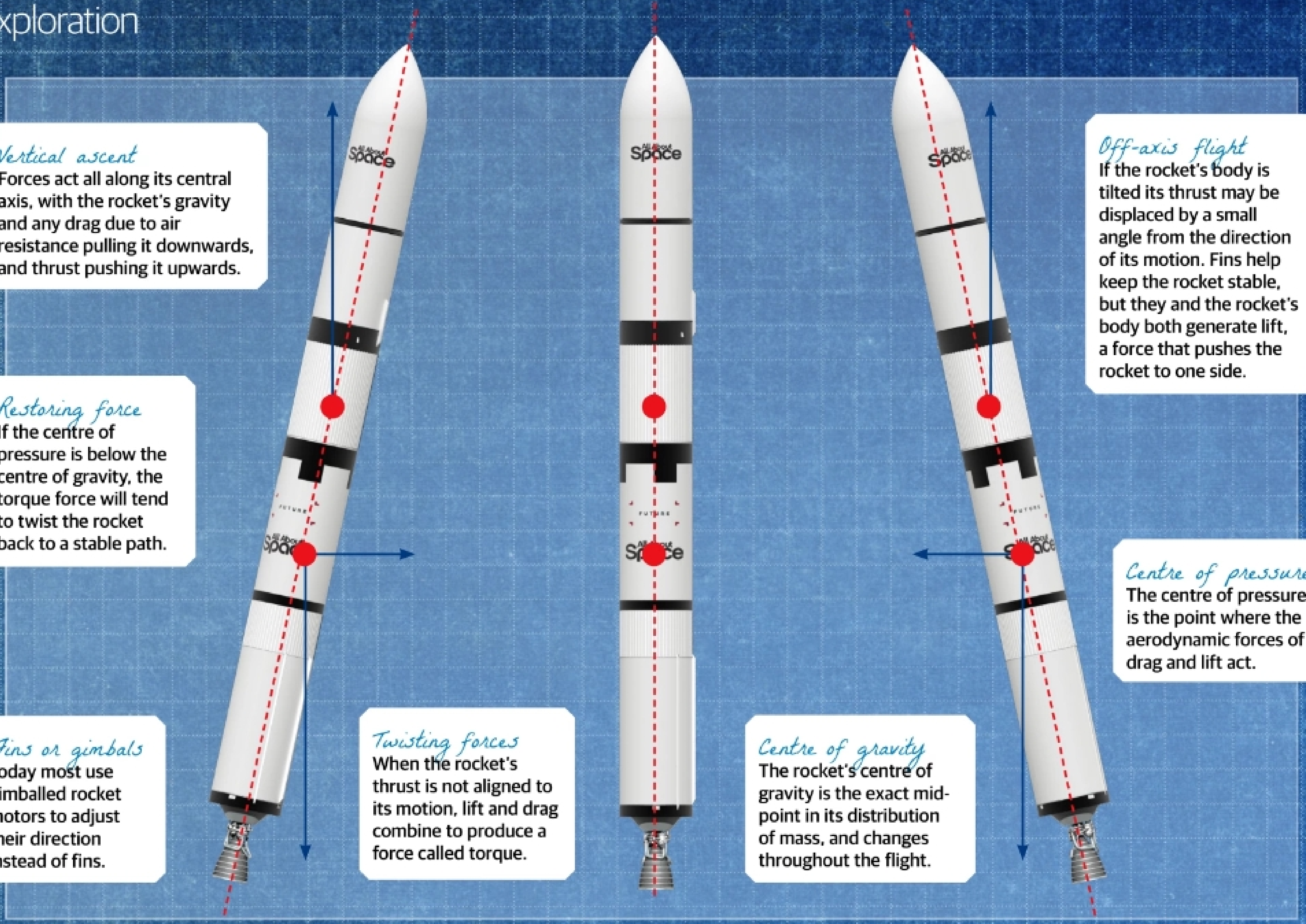
> "Rockets generate a force in one direction, called thrust, by the principle of action and reaction"

or in fireworks, rockets generate a force in one direction, called thrust, by the principle of action and reaction – exhaust fumes released by explosive chemicals are pushed out of the back of the rocket at high speed, and as a result the rocket is pushed in the other direction, regardless of any surrounding medium. The key to using rockets in space is simply to carry another chemical called an 'oxidant' that can perform the same role as oxygen in the Earth's air and allows the fuel to combust.

The first person to seriously study the rocket's potential for space travel, a Russian schoolteacher and amateur scientist called Konstantin Tsiolkovsky, first published his conclusions in 1903. He correctly identified the moment of launch as one of the biggest challenges – the moment where the rocket has to carry all the fuel and oxidant it needs to reach space – as its weight is at a maximum and a huge amount of thrust is needed simply to get it moving at all. As the rocket gets underway it sheds mass through its exhaust, so its weight is reduced and the same amount of thrust will have a greater effect in terms of accelerating the rest of the rocket. Tsiolkovsky came up with various rocket designs and concluded that the most efficient set-up was a vertically launched vehicle with several 'stages' – each a self-contained rocket that could carry the stages above it for a certain distance before exhausting its fuel, detaching and falling away. This principle, still widely used today, reduces the amount of 'dead weight' that needs to be carried all the way into space.

Tsiolkovsky devised a complex equation that revealed the necessary thrust force needed for any given rocket manoeuvre, and the 'specific impulse' – how much thrust is generated per unit of fuel – needed for a rocket to reach space. He realised that the explosive rocket propellants of his time were far too inefficient to power a space rocket, and argued that liquid fuels and oxidants, such as liquid hydrogen and liquid oxygen, would ultimately be needed to reach orbit and beyond. Although he did not live to see his work recognised, Tsiolkovsky's principles still underpin all of modern rocketry.

The Delta II rocket's first-stage core was assisted by nine separate solid-rocket boosters during launch



Vertical ascent
Forces act all along its central axis, with the rocket's gravity and any drag due to air resistance pulling it downwards, and thrust pushing it upwards.

Restoring force
If the centre of pressure is below the centre of gravity, the torque force will tend to twist the rocket back to a stable path.

Fins or gimbals
Today most use gimballed rocket motors to adjust their direction instead of fins.

Twisting forces
When the rocket's thrust is not aligned to its motion, lift and drag combine to produce a force called torque.

Centre of gravity
The rocket's centre of gravity is the exact mid-point in its distribution of mass, and changes throughout the flight.

Off-axis flight
If the rocket's body is tilted its thrust may be displaced by a small angle from the direction of its motion. Fins help keep the rocket stable, but they and the rocket's body both generate lift, a force that pushes the rocket to one side.

Centre of pressure
The centre of pressure is the point where the aerodynamic forces of drag and lift act.

2

Taking flight

Rockets must delicately balance and control powerful forces in order to make it through Earth's atmosphere into space

A rocket generates thrust using a controlled explosion as fuel and oxidant undergo a violent chemical reaction. Expanding gases from the explosion are pushed out of the back of the rocket through a nozzle – a specially shaped exhaust that channels the hot, high-pressure gas created by combustion into a stream that escapes from the back of the nozzle at hypersonic speeds, more than five-times the speed of sound.

Isaac Newton's third law of motion states that every action has an equal and opposite reaction, so the 'action' force that drives the exhaust out of the rocket nozzle must be balanced by an equal and opposite force pushing the rocket forwards. Specifically this force acts on the upper wall of the 'combustion chamber', but since the rocket motor is integral to each rocket stage, we can think of it acting on the rocket as a whole.

Although the forces acting in both directions are equal, their visible effects are different because of another of Newton's laws which explains how objects with greater mass need more force to accelerate them by a given amount. So while the 'action' force rapidly accelerates a small mass of exhaust gas to hypersonic speeds each second, the equal 'reaction' force produces a far smaller acceleration in the opposite direction on the far greater mass of the rocket.

As the rocket gains speed, keeping the direction of motion closely aligned with the direction of thrust is critical – gradual adjustments are needed to steer the rocket towards an orbital trajectory, but a severe misalignment can send the rocket whirling out of control. Most rockets, including the Falcon and Titan series and the Saturn V Moon rocket, steer using 'gimballed' engines, mounted so that the entire rocket motor can pivot and vary the direction of its thrust from moment to moment. Other steering options include using external vanes to deflect the exhaust gases as they escape the rocket engine – most effective with solid-fuelled rockets that lack a complex motor – and auxiliary engines – small 'thruster' rockets mounted on the sides of the rocket stage.

> "Keeping the direction of motion closely aligned with the direction of thrust is critical"

© NASA; Adrian Mann; Belterz

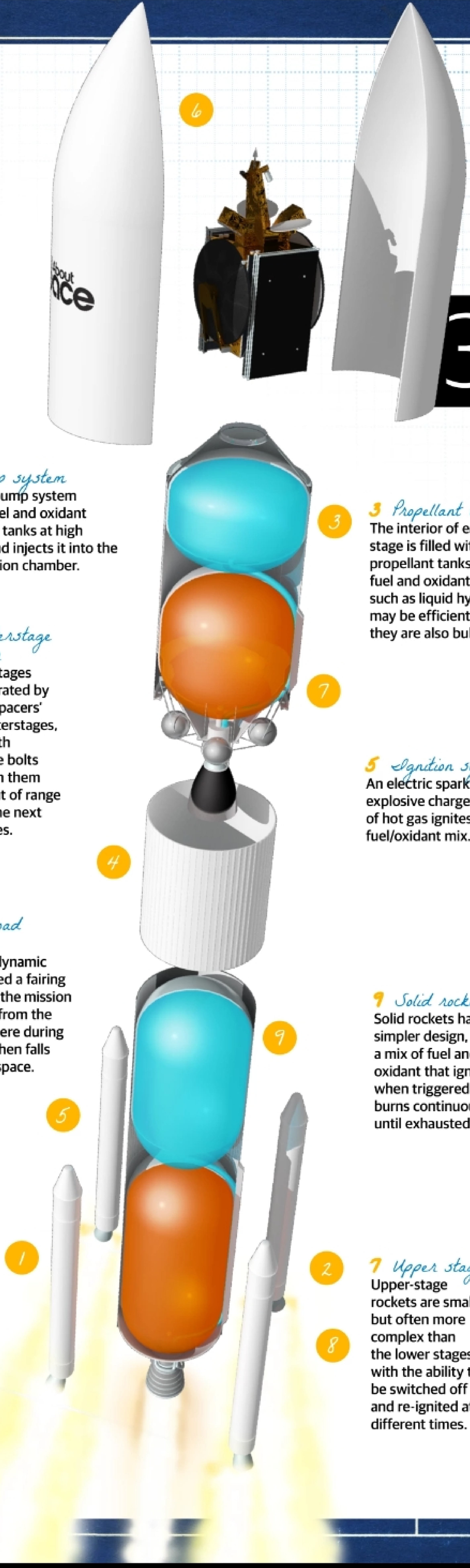
3 How a rocket's motors work

Rocket engines are complex machines that must endure ferocious heat and pressure

Modern rocket motors have come a long way from fireworks. Relatively simple solid rockets, most often used as boosters to provide extra thrust at launch, still rely on the same basic principle of igniting a tube containing a combustible mix of fuel and oxidant. Once ignited, a solid rocket will continue to burn until its fuel is exhausted, but the rate at which fuel is burnt – and therefore the amount of thrust – can be controlled by changing the amount of surface exposed to ignition during different times in the rocket's flight. This can be done by packing the fuel/oxidant mix with a hollow gap down the centre, running along the length of the rocket. Depending on the profile of this gap, which may be circular or star-shaped, for instance, the amount of exposed surface will change during the flight.

The more widespread liquid-fuelled rockets are far more complex. Typically they involve a pair of propellant tanks – one each for the fuel and the oxidant – connected to a combustion chamber through a complex maze of pipes. High-speed turbopumps driven by their own independent motor systems are used to deliver liquid propellant into the chamber through an injection system. The rate of supply can be throttled up or down depending on requirement, and fuel can be injected as a simple jet or a fine spray. Inside the combustion chamber an ignition mechanism is used to begin combustion – this may be a jet of high-temperature gas, an electric spark or a pyrotechnic explosion. Rapid ignition is critical – if too much fuel/oxidant mixture is allowed to build up in the combustion chamber than a delayed ignition can generate enough pressure to blow the rocket apart, a catastrophic event that rocket engineers laconically refer to as a 'hard start' or 'rapid unscheduled disassembly' (RUD).

The detailed design of a liquid rocket stage can vary a lot depending on its fuel and other requirements. Some of the most efficient propellants are liquefied gases such as liquid hydrogen, which is only stable at very low temperatures – around -253 degrees Celsius (-423 degrees Fahrenheit). Once loaded aboard the rocket these 'cryogenic' propellants must be stored in heavily insulated tanks. Some rockets avoid the need for an ignition mechanism using 'hypergolic' propellants that ignite spontaneously on contact with each other.



1 Boosters
Solid rockets make ideal boosters for use during liftoff. Strapped around a central liquid-fuelled 'first stage', they fall away when exhausted.

2 Pump system
A turbopump system draws fuel and oxidant from the tanks at high speed and injects it into the combustion chamber.

3 Propellant tanks
The interior of each stage is filled with large propellant tanks for fuel and oxidant – fuels such as liquid hydrogen may be efficient, but they are also bulky.

4 Interstage adaptor
Rocket stages are separated by empty 'spacers' called interstages, fitted with explosive bolts that push them safely out of range before the next stage fires.

5 Ignition system
An electric spark, explosive charge or jet of hot gas ignites the fuel/oxidant mix.

6 Payload fairing
An aerodynamic case called a fairing protects the mission payload from the atmosphere during launch, then falls away in space.

9 Solid rockets
Solid rockets have a simpler design, with a mix of fuel and oxidant that ignites when triggered and burns continuously until exhausted.

7 Upper stage
Upper-stage rockets are smaller but often more complex than the lower stages, with the ability to be switched off and re-ignited at different times.

8 Combustion chamber
Fuel and oxidant undergo violent combustion, creating expanding gases that are forced out through a shaped nozzle at the bottom. This generates upward thrust in the rocket motor itself.

4

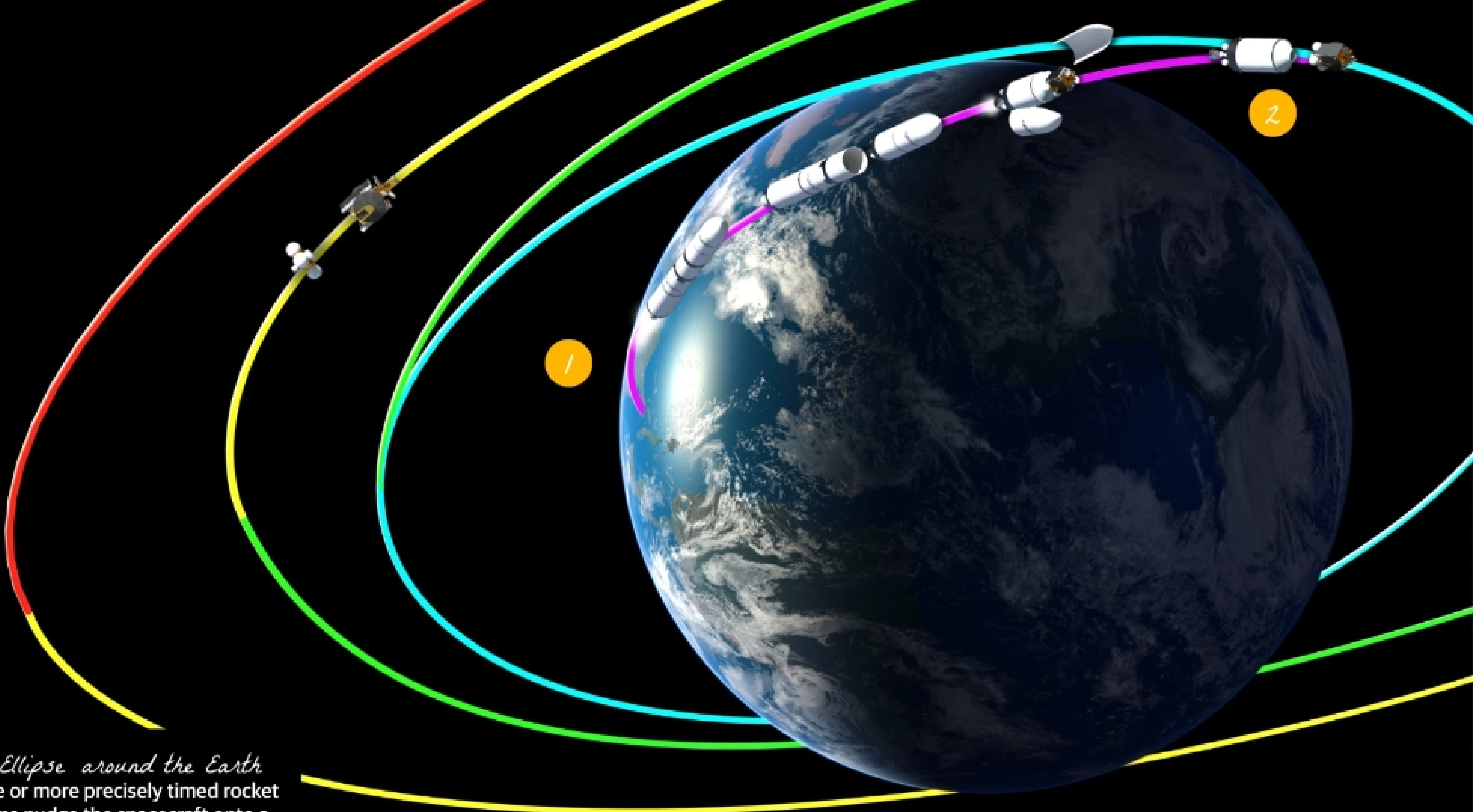
Interplanetary travel

Rockets are the key to exploring our Solar System – but how do they go from orbit to deep space?

Below: Nuclear thermal rockets are a hypothetical way of generating large amounts of thrust for sustained periods – they could one day shorten the journey time to other planets from months to weeks

The first stage of any spaceflight involves launch from Earth's surface into a relatively low orbit around 200 kilometres (124 miles) up, above the vast majority of the atmosphere. Here gravity is almost as strong as it is on the surface, but friction from Earth's upper atmosphere is very low, so if the uppermost stage of the rocket is moving fast enough it can maintain a stable circular or elliptical trajectory where the pull of gravity and the vehicle's natural tendency to fly off in a straight line cancel each other out.

Many spacecraft and satellites travel no further than this low-Earth orbit (LEO), but those destined to leave Earth entirely and explore the wider Solar System need a further boost in speed to reach escape velocity – the speed at which they can never be pulled back by our planet's gravity. The escape velocity at Earth's surface – 11.2 kilometres (6.9 miles) per second – is about 50 per cent faster than the typical speeds of objects in LEO. It gets lower at a greater distance from Earth, and probes bound for interplanetary space are often first injected into elongated or elliptical orbits by a carefully timed burst of thrust from an upper-stage rocket, which may remain attached to the spacecraft for the rest of its interplanetary flight. In such an orbit the spacecrafts' distance from Earth can range from hundreds to thousands of kilometres, and its velocity will also vary, reaching a maximum when the spacecraft is closest to Earth, a point called perigee, and slowing down further out.



1 Low-Earth orbit
Directly after launch, a space probe usually enters a roughly circular low-Earth orbit a couple of hundred kilometres above the Earth.

2 Ellipse around the Earth
One or more precisely timed rocket burns nudge the spacecraft onto a more elliptical trajectory that varies in distance from Earth.

© NASA; SpaceX; Adrian Mann

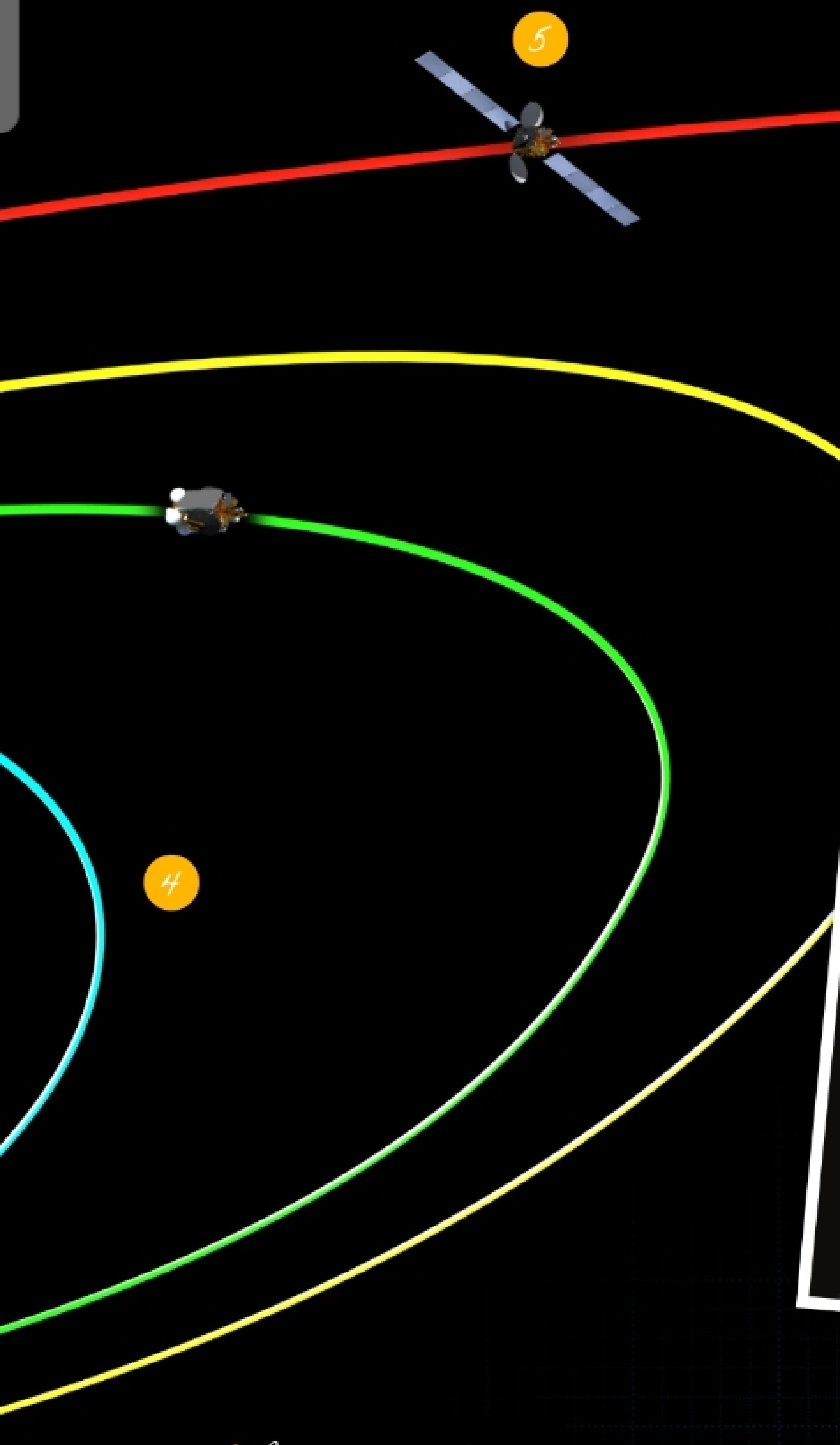
Surprisingly, however, the critical rocket burn used to escape into interplanetary space is usually made when the spacecraft is near perigee. This is due to the so-called 'Oberth effect', an unexpected property of rocket equations that means a rocket is more efficient when it is moving at higher velocity. One way to understand this is that burning a spacecraft's fuel allows the engine to utilise not only its chemical energy, but also its kinetic energy, which is greater at higher speeds. On balance, the additional rocket thrust needed to reach escape velocity from a low altitude at higher speed is less than that needed to escape from a high altitude when moving at a lower speed.

Spaceflight engineers and mission planners often refer to the 'Delta-v' required to accomplish a specific flight manoeuvre, such as a change in orbit. Strictly speaking the term 'Delta-v' means change in velocity, but engineers use it specifically as a measure of the amount of 'impulse', or thrust force over time, needed to accomplish a manoeuvre. Broadly speaking, missions are planned around a 'Delta-v budget' – how much thrust they can generate for how long using the spacecraft's onboard fuel supplies.

Sending a spacecraft from one planet to another with minimum Delta-v requirements involves injecting it into an elliptical orbit around the Sun, called a Hohmann transfer orbit. The spacecraft travels along a segment of the elliptical path that resembles a spiral track between the orbits of the two planets, and requires no further thrust along its journey. On arrival at its target object it may use gravity alone to enter its final orbit, or it may require a burst of rocket thrust in the opposite direction – usually accomplished by simply turning the spacecraft around in space and firing the motor – before it can achieve a stable orbit.

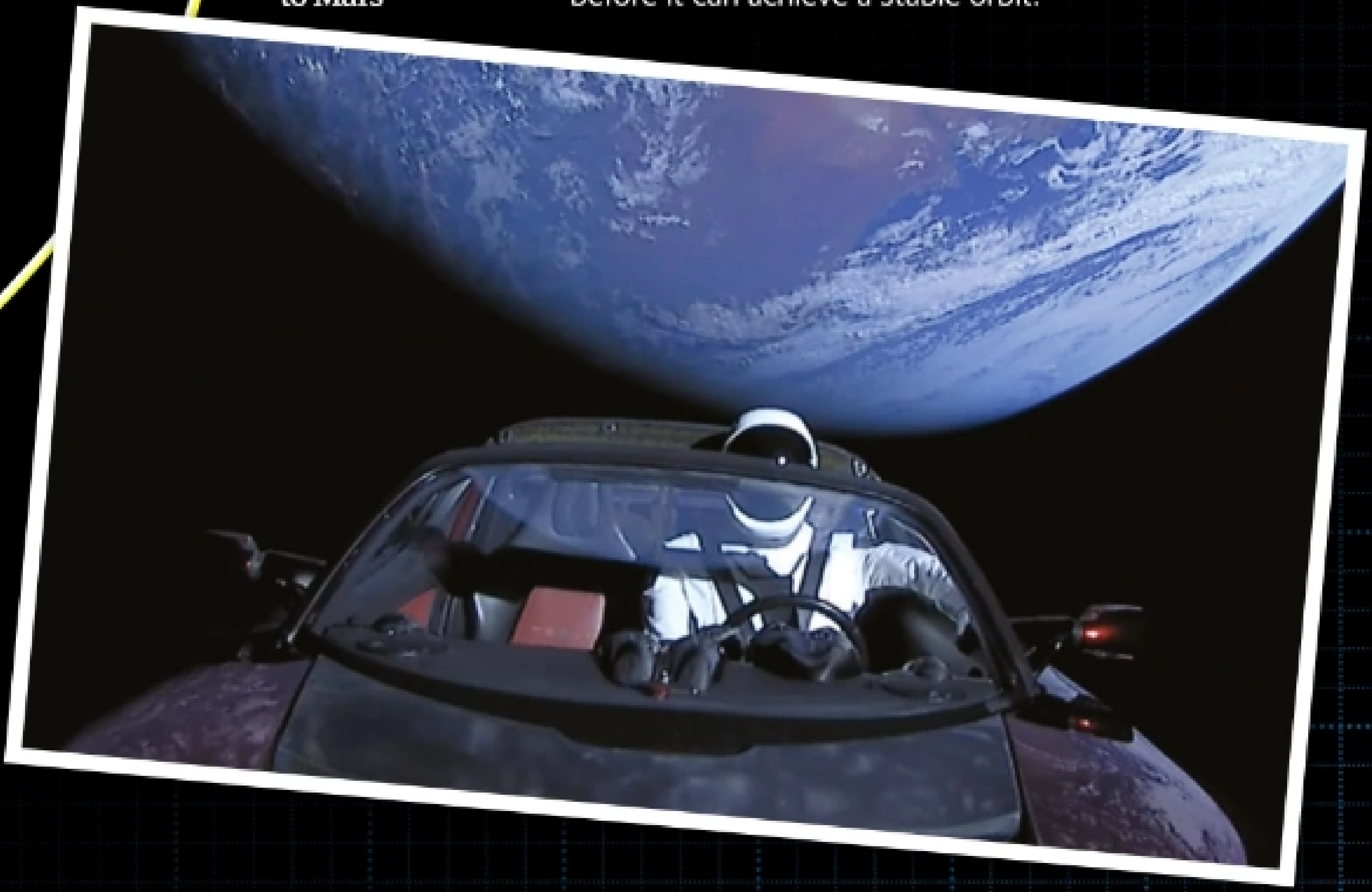
4 *Close burn*
The Oberth effect allows a spacecraft's rockets to deliver more thrust for a set amount of fuel when it is already moving at high speed and close to Earth.

5 *Hohmann transfer orbit*
A final burn allows the probe to break free from Earth on a trajectory that looks spiral from our point of view, but is actually a segment of an elliptical orbit around the Sun.



3 *Picking up speed*
In an elliptical transfer orbit the probe moves more slowly at greater distance from Earth, and much more quickly around its closest approach.

Below: In February 2018 the SpaceX Falcon Heavy rocket demonstrated its power by putting a Tesla Roadster in a transfer orbit to Mars



> *"Burning fuel allows the engine to utilise not only chemical energy, but also kinetic energy"*

Deep Space

Distant galaxies, dwarf planets, alien worlds and exploring the edges of the observable universe

58 Have we found Galaxy X?
Are astronomers any closer to pinpointing the mysterious object packed with dark matter?

66 Water worlds
They may be plentiful in the Milky Way galaxy, but scientists now think that they may not be suitable for life

72 Mystery of the space roar
When scientists put their ear to the early universe, they found it yelled back - have we finally found the cause?

80 Does space have a final dimension?
There could be more to the universe than meets the eye with extra facets beyond space and time

88 Beyond deep space
How technology is helping us peer to the edges of the observable universe

"It's clear that the quest for Galaxy X is about to get a lot more interesting"

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Mystery of the space roar

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Space's final dimension

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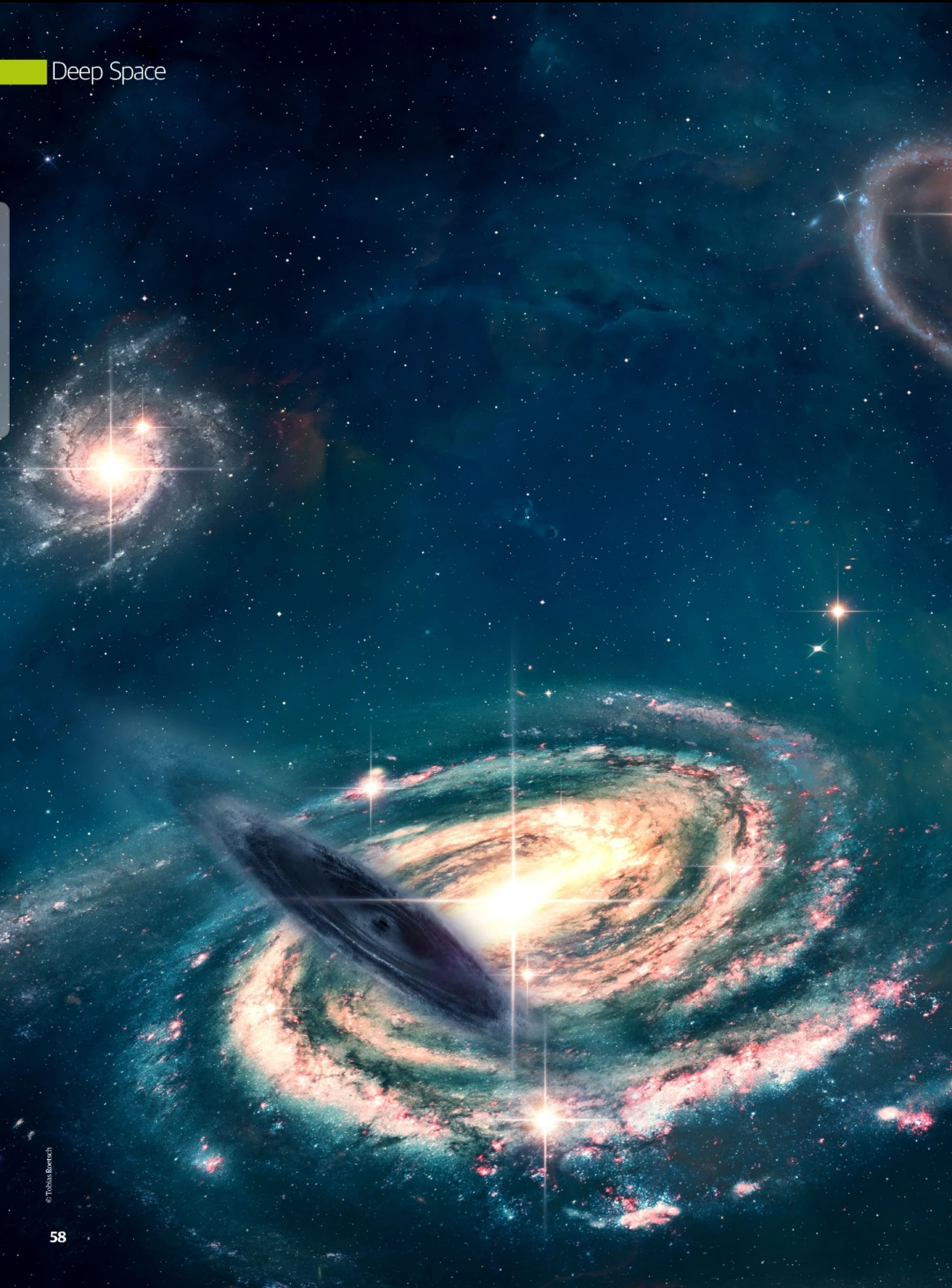
Water worlds



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HAVE WE FOUND GALAXY X?

Are astronomers any closer to pinpointing the mysterious object packed with dark matter?

Reported by Leo Bear-McGuinness & Ian Evenden

We like to think of our galaxy as a lone wanderer through the cosmos, solitarily spinning in the intergalactic gloom. But we are not alone in the universe – we have company along for the ride. Dwarf galaxies surround our own galactic swirl. Staying within 1.4 million light years of our galaxy's rim, dozens of these petite galaxies have already been discovered. But astronomers believe there is at least one more out there, a cluster of unknown matter hidden at the edge of the Milky Way: Galaxy X.

Theorised for years, Galaxy X is thought to be around one per cent the mass of the Milky Way, 300,000 light years from its centre and consisting almost entirely of dark matter, the mysterious substance said to make up 23 per cent of the universe's mass. But it's still just a theory. While astronomers have the mathematic calculations to believe the secretive galaxy exists, they've yet to find any concrete evidence. Despite their best efforts, it has stubbornly remained theoretical. But all that might soon change in the weeks to come…

"I started looking for Galaxy X about ten years ago, so I feel quite old talking about this," quips Sukanya Chakrabarti, an assistant professor of physics at the Rochester Institute of Technology. After authoring a paper on the potential existence of the galaxy in 2009, Chakrabarti has since become the world's lead investigator in the hunt for Galaxy X. And as she admits, it's been a long quest.

Back in 2009, she and fellow astronomer Leo Blitz analysed variations in the distribution of gas found at the edge of the Milky Way, and they couldn't easily explain what they found. "It showed very large perturbations on the outskirts of the edges of our galaxy," says Chakrabarti. "This is well beyond the solar circle, so you wouldn't expect such large perturbations." Now, at this stage in any other hunt for a celestial object, Chakrabarti might have turned to telescopic data and looked for the disturbance herself. But with Galaxy X, nothing is ever simple.

"I didn't make life easy for myself," she jokes. "The calculations preferred a co-planar merger – that is, the dwarf galaxy was orbiting roughly in the same plane as the Milky Way. And that means that if you were trying to look for it, you'd be having to deal with the dust obscuration close to the plane of the galaxy." Unlike many dwarf galaxies, Galaxy X didn't seem to be hovering above or below the Milky Way's plane, which would make it easier to see. Instead, the elusive system appeared to be

Above: The distribution of dark matter in the centre of the giant galaxy cluster Abell 1689, containing about 1,000 galaxies and trillions of stars, as captured by the Hubble Space Telescope

Right: Urbain Le Verrier, the French astronomer who predicted the location of Neptune

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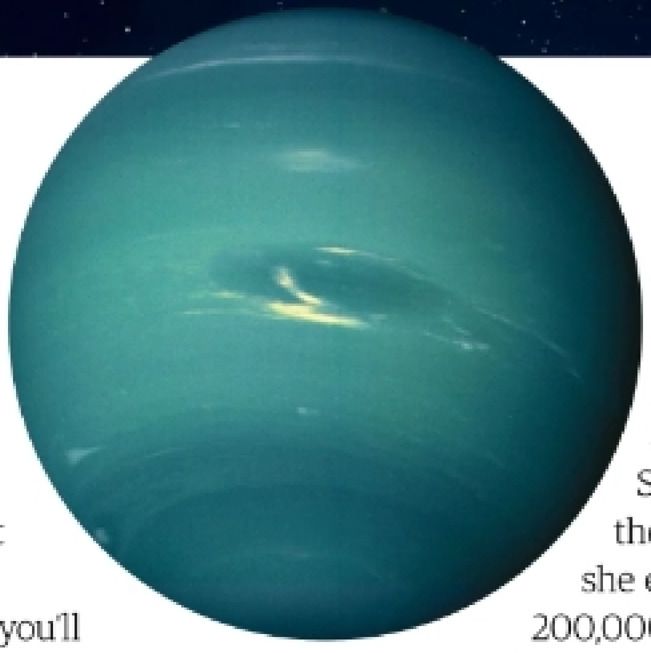


hidden right at the edge of the Milky Way's disc, and so would be completely obscured by the giant expanse of dust and gas between it and Earth.

"So, if you look above the plane, you'll see other dwarf galaxies which are easily visible because they're well off the plane of the galaxy," says Chakrabarti. "But if you're looking through dust, it's like looking through a smoke screen. So that's why a lot of these surveys for dwarf galaxies have largely avoided the galactic plane. And that's also why most of the discoveries of dwarf galaxies so far have been well above it."

Undeterred, Chakrabarti opted for a different search tactic. Instead of looking for Galaxy X directly, she studied everything else in its supposed region and scraped information about the dwarf galaxy's behaviour through what couldn't be seen. These experiments began with computer simulations of the Milky Way and its known dwarf galaxies, and perturbations at the simulated galaxy's edge soon showed up. "I included the gravitational effects of the three most massive dwarf galaxies of the Milky Way – these are the Large Magellanic and Small Magellanic Clouds and the Sagittarius Dwarf Galaxy," she explains. Floating less than 200,000 light years from Earth, these satellite galaxies and their millions of stars can be seen from the Southern Hemisphere and even helped early Polynesian cultures navigate the seas. "I gave them those orbits to see how close a perturbing dwarf galaxy would have to get to produce the observed disturbances in the outer gas disc of the Milky Way. They were the most realistic simulations that I could do," she adds.

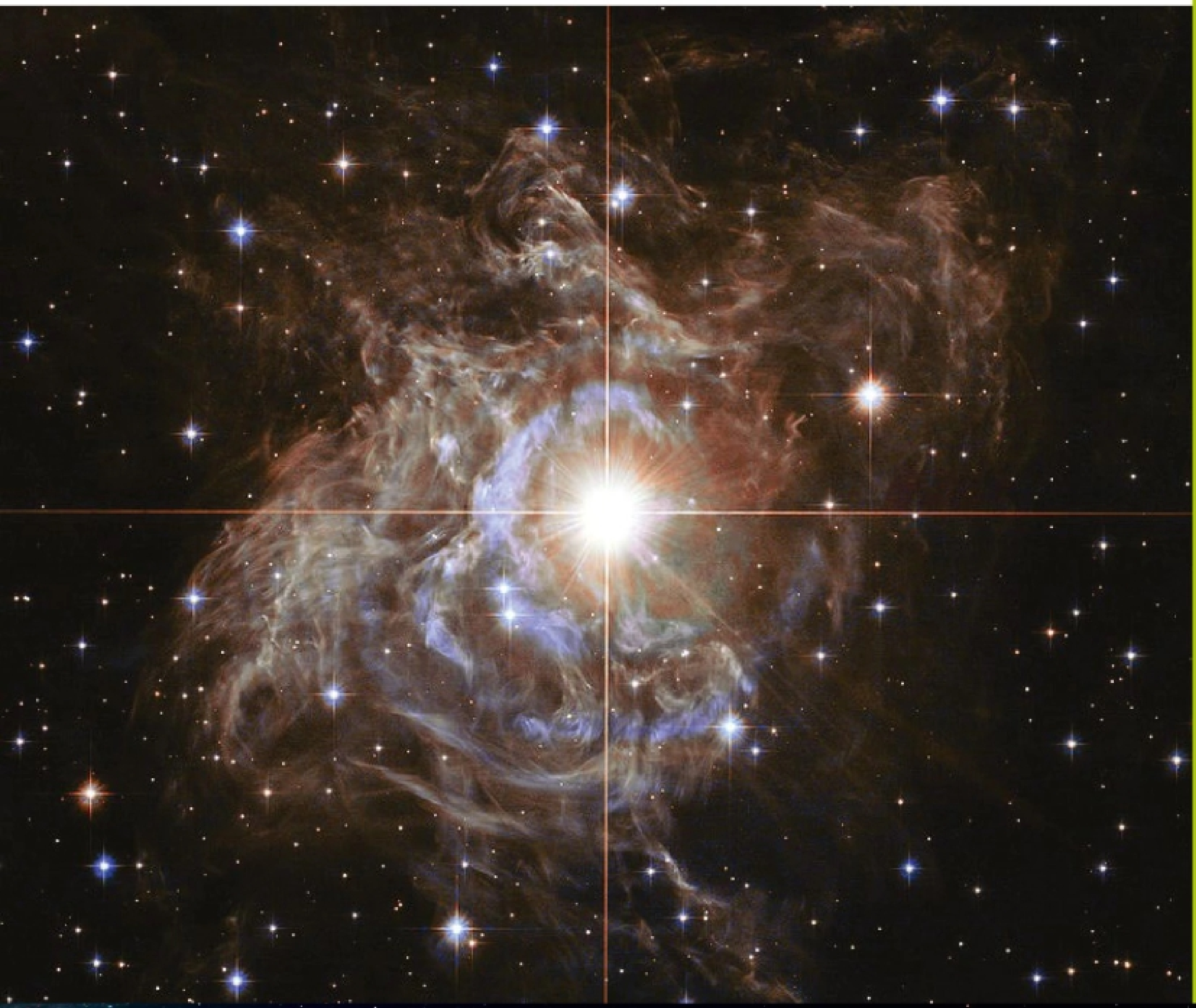
"And I found that even after including the gravitational effects of all the known players of the Milky Way, you still couldn't explain the observed disturbances in the outer gas disc. So I concluded that we needed a new dwarf galaxy that had not yet been identified in 2009. And that's really when I put on my observer's hat and started to look for it myself."

Her observer's hat donned and curiosity piqued, Chakrabarti spent the next few years hunting

Left: Neptune's north pole, as seen by NASA's Voyager 2

Below: A Cepheid variable star, a type of star detected within Galaxy X, taken in the Milky Way by the Hubble Space Telescope

> "Even after including the gravitational effects of all the known players of the Milky Way, you still couldn't explain the disturbances" **Sukanya Chakrabarti**



Dark matter galaxies

Though hypothetical, these galaxies could be real examples

Dragonfly 44

This strange galaxy has around the same mass as the Milky Way, yet hardly any stars shine from its disc – only one per cent the number seen in our home galaxy. This means it emits only one per cent of the light too, making it difficult to identify.

Dark matter	Visible matter
0.1%	99.9%

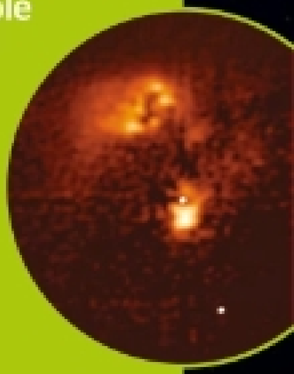
Segue 3

Smaller galaxies tend to be proportionately richer in dark matter. The galaxy with the lowest known mass, Segue 3 in the constellation of Pegasus, has 600-times more dark matter than normal matter. A more usual ratio is 5:1.

Dark matter	Visible matter
98.83%	0.17%

HE0450-2958

A quasar apparently floating freely in space. It may be a supermassive black hole ejected from a nearby star-forming galaxy, a misidentification of a luminous galaxy as a quasar or a host galaxy so dim the quasar completely outshines it.

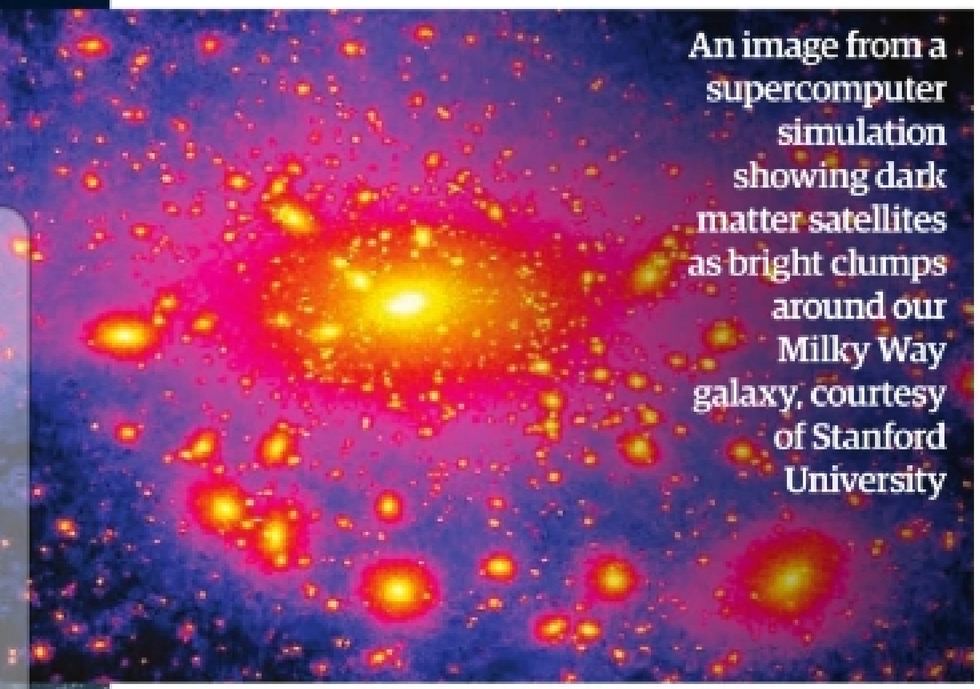


Dark matter	Visible matter
??%	??%

NGC 1052-DF2

This ultra-diffuse galaxy in Cetus is one of two that appear to have little or no dark matter. Despite this the galaxies hold together, possibly suggesting that what we call 'dark matter' may be an unknown effect of normal matter's gravity.

Dark matter	Visible matter
0.25%	99.75%



An image from a supercomputer simulation showing dark matter satellites as bright clumps around our Milky Way galaxy, courtesy of Stanford University

> “To be convinced that a distant galaxy is real, a sample of stars at a particular distance on the sky must be convincing” **Alice Quillen**

through spectroscopic surveys of space, searching for any clue that could lead her to the missing phenomena. And, in 2015, she and her colleagues found just that: four bright, variable stars right where Galaxy X should be. It was just the kind of sign they needed.

“To find a dwarf galaxy, you try to find stars that are in it,” explains Alice Quillen, a professor of physics and astronomy at the University of Rochester. Lending her significant expertise to the Galaxy X quest, Quillen helped write the 2015 paper that further pinpointed the dwarf galaxy on the map. “Dwarf galaxies are very diffuse,” she adds. “So to be convinced that a distant galaxy is real, a sample of stars at a particular distance on the sky must be convincing.” And fortunately for Quillen and her colleagues, the stars found in 2015 were very convincing, at least for them.

“We found that they were all coherently receding,” says Chakrabarti. “That is, they were all moving away from us with roughly the same velocity, which was comparable to what you expected from the dynamical models. So we believed that these stars could either be part of Galaxy X or part of a tidal stream that was produced by it.”

Perturbations in outer space, a hypothesised cause and calculations to prove its existence; in many ways, Chakrabarti’s quest for Galaxy X is a mirror story to Urbain Le Verrier’s discovery of Neptune in the 1800s. Like Chakrabarti, the French astronomer first observed discrepancies with celestial orbits. Uranus’ elliptical path didn’t seem to make sense if there wasn’t another hidden planet affecting its trajectory. Sure

The Milky Way

The galaxy we call home is hard to map, since we can’t observe it from outside

You are here
Our Solar System lies in the Orion Arm of the Milky Way’s spiral, approximately 26,000 light years from the galactic centre.

Bullet cluster
This recent galactic merger’s gravitational mass is not where it should be based on observations, so something invisible must be having an effect on its gravity.

Galaxy X?
On the other side of the galactic centre, hidden by the disc, the proposed location of Galaxy X is 290,000 light years from us.

Seeing the unseeable

Although yet unobserved, there are some telltale signs of Galaxy X

Perturbed edge of Milky Way

Something was disturbing the hydrogen gas at the edge of our galaxy. These can reveal the distance, location and mass of a satellite galaxy that can't be seen in visible light. The gas can be mapped with radio telescopes, and mathematical analysis of this data reveals the galaxies.

Stars that brighten and dim

Four Cepheid variable stars were found 300,000 light years away using the VISTA infrared telescope, which can see through some of the dust at our galaxy's core. The Milky Way only extends 48,000 light years in their direction, so they must be in another galaxy.

Smith's Cloud

A massive cloud of gas that withstood a pass through the Milky Way 70 million years ago and is now coming back for more. To have survived, it is hypothesised, it may be embedded in its own dark-matter halo. It will hit the Perseus Arm in roughly 30 million years.

Milky Way dark-matter halo

As much as 95 per cent of our galaxy is made up of dark matter, extending well beyond the visible galaxy into intergalactic space. It is densest in the centre, roughly spherical and gets less dense as distance from the centre increases.

Large Magellanic Cloud

As our largest satellite galaxy approaches, its dark-matter halo interacts with the Milky Way's, a phenomenon known as its 'dark matter wake'. Scientists can see this in changes to the movements of stars in the LMC's direction.

Andromeda Galaxy

Although it appears larger than the Milky Way, Andromeda weighs about the same because it has less dark matter. This will become very important when the two galaxies merge in 4.5 billion years' time.

Other satellite galaxies

Galaxies such as the Sagittarius Dwarf and Small Magellanic Cloud each have their own dark-matter haloes. Their mass increases as the galaxies merge.

© Tobias Roetsch; Kazantzidis

Catching a GLIMPSE of Galaxy X

The Galactic Legacy Infrared Mid-Plane Survey Extraordinaire, or GLIMPSE, uses the Spitzer space telescope to survey the galactic plane, meaning that it will cover the area Galaxy X is expected to be in.

Spitzer is an infrared telescope, meaning it can pick up on radiation passing through the galactic core, an area that blocks visible light and generates a lot of radio waves that can interfere with observations.

Spitzer was launched by NASA in 2003 from Cape Canaveral with a planned mission lasting 2.5 years, but is still operational today. Subsequent launches of observational telescopes, such as the Wide-field Infrared Survey Explorer (WISE) in 2009 and the James Webb Space Telescope in 2021, have – and will – increase our ability to hunt out Galaxy X and others like it.

> “The kind of dwarf galaxies that we've been finding lately are much fainter than we had ever hoped we’d be able to find” **Sukanya Chakrabarti**

Right: The Small Magellanic Cloud, a dwarf galaxy captured in infrared light from the Herschel Space Observatory, a European Space Agency-led mission, and NASA's Spitzer Space Telescope

Below: The Large Magellanic Cloud, a satellite galaxy to the Milky Way, as seen from NASA's Spitzer Space Telescope

enough, Le Verrier's prediction was right, and Neptune was found within one degree of his calculations. It was the first time in history that any hidden object had been discovered just through analysis of its gravitational imprints on another celestial body.

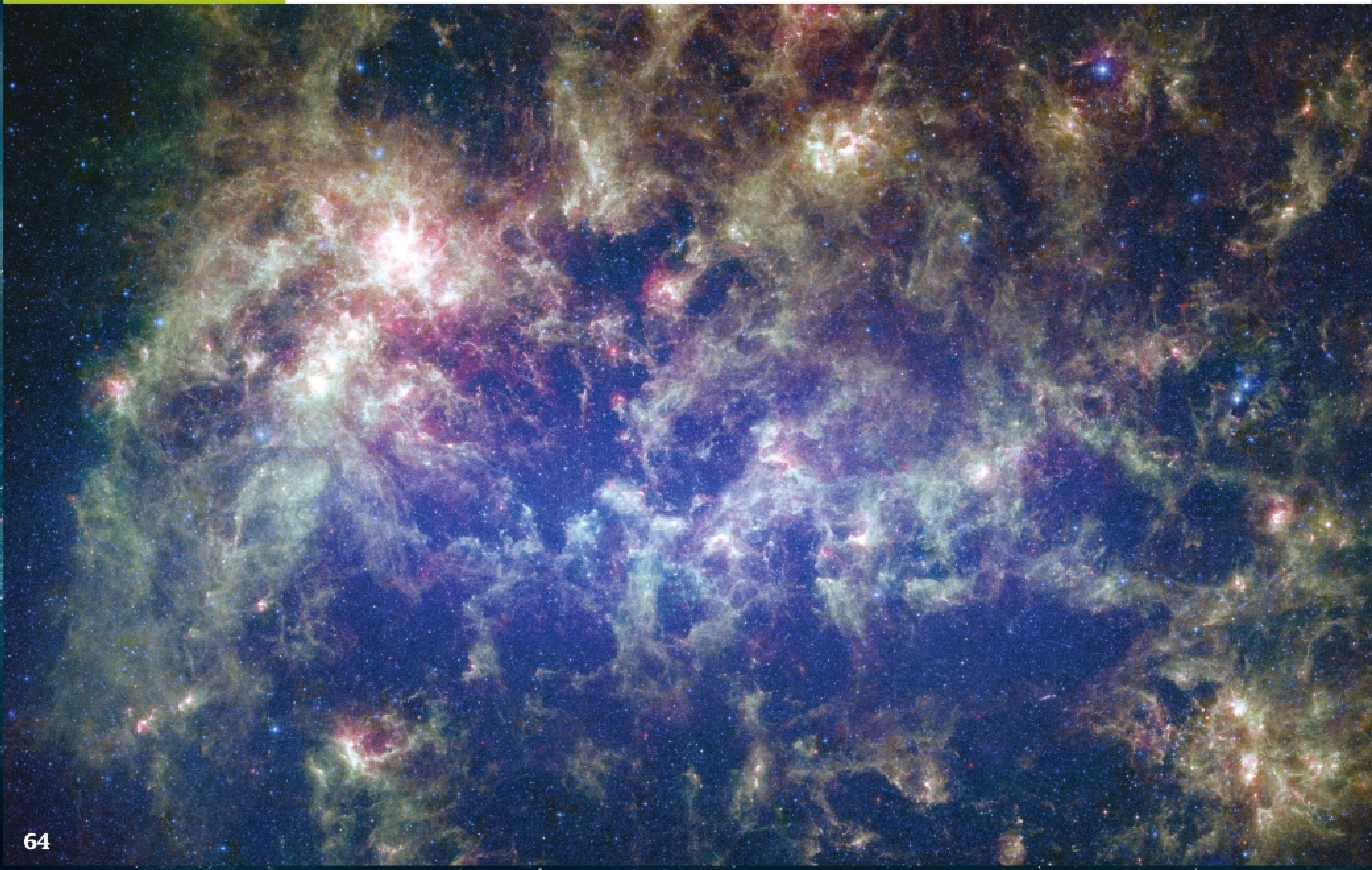
But Galaxy X is different; proof of its existence has yet to be published. And without this hard evidence, the scientific community has been a little less accepting than it was for Le Verrier. Some astronomers have even rebuked the existence of the galaxy altogether. Writing in the *Astrophysical Journal Letters* in 2015, one group of scientists discredited the stars found by Chakrabarti and Quillen as “spotted objects” and claimed that there was no evidence for a dwarf galaxy at all. Suffice to say, Chakrabarti was less than pleased about the community's scepticism.

“I can't say that I was thrilled about it,” she jokes. “Scientists are sceptical in general and discoveries are hard to prove, so this was probably no different in that sense.” Healthy scepticism or not, the challenge quickly deepened Chakrabarti's resolve. Now she and her colleagues had both a galaxy to prove real, and a paper to prove wrong. More evidence was desperately needed and, in 2017, they found it.

“We did refine several things in our 2017 paper,” Chakrabarti explains. “In addition to getting light curves to identify the variable star candidates, we also got spectra [more data from the near-infrared spectrum]. And by looking at the spectra we got a completely independent piece of information, independent to the light curves. And that is really why we did it, because we wanted it to be found in a very unbiased way.”

With this added information Galaxy X was brought back to the realms of possibility, and the quest reinvigorated. The 2015 challenger paper had rocked the hunt's foundations, but they were now rebuilt stronger than ever. “That's just the nature of science,” Chakrabarti admits. “You are continually trying to refine what you did.” And so the search marches on, ten years after it first began. But is there any hope that Galaxy X's smoking gun could be found before the pursuit reaches its next decade? Without giving much away, Chakrabarti hints that such a revelation could be just around the corner.

“There might be, on the horizon, some more news about Galaxy X soon,” she confides. “We're



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at this stage right now where we've gone through a particular candidate and we're in the process of writing the paper, which is about 50 per cent done." But while a new candidate could lend the quest some more credibility, a photograph would be the trophy that could finish the hunt altogether. Unfortunately, any dark-matter object obscured by half the Milky Way would be a challenge to image. But as the recently released first picture of a black hole demonstrates, even one of the most elusive, light-devouring objects in the universe can now be visualised. Of course, that achievement was no simple feat. The black hole image was constructed from radio waves that travelled 54 million light years to be sourced from eight different observatories across the world. But, time and cost aside, is there anything stopping Galaxy X from receiving the same sort of photo shoot?

After posing the question to Chakrabarti, the astronomer clearly becomes animated with classified knowledge, and stifles any announcements before they slip out. "I'm having difficulty answering the question, because that's one of the things I've been writing about right now. So what I want to say at the moment is that the chances are very good.

"Seeing it in radio would mean that it has to have gas, but seeing it in the optical is very possible now with the new surveys that are ongoing. And the kind of dwarf galaxies that we've been finding lately are much fainter than we had ever hoped we'd be able to find. I think the chances of getting an optical image are really, really good, so stay tuned on that. There will probably be some news on that very, very shortly - some big news."

While Chakrabarti remains tight-lipped, it's clear that the quest for Galaxy X is about to get a lot more interesting. And as the dwarf system is thought to consist almost entirely of dark matter, any information about its nature could have far-reaching revelations about the mysterious substance and its role in the universe. But for Chakrabarti and her colleagues, the most tantalising prospect of Galaxy X is the galaxy itself. Sought after for over a decade, any subsequent facts and figures from its discovery will undoubtedly pale in comparison to the actual find. X may mark the spot for future research and astronomical studies, but after years of searching, just the confirmation of another companion in our endless drift through the universe would be enough to make both journeys worthwhile.

Below: **The first-ever image of a black hole, as taken by the Event Horizon Telescope**

WATER WORLDS

They may be plentiful in the Milky Way galaxy, but scientists now think that they may not be suitable for life

Reported by Lee Cavendish

Imagine a world covered entirely in water – no land separating vast oceans. A recent discovery announced at the Goldschmidt Conference in Boston, Massachusetts, United States, has found that these 'water worlds' are more common than previously thought. This discovery comes courtesy of data collected by two very diligent missions that have studied the cosmos for years now – the European Space Agency's Gaia and NASA's Kepler. Of the 4,000 confirmed or candidate exoplanets, 35 per cent were found to be water worlds.

The first discovery of exoplanets was announced in 1992 with the planets PSR B1257+12c and 12d. They were found to be orbiting a pulsar 2,300 light years away in the constellation of Virgo. A third planet, PSR B1257+12b, was found orbiting the same pulsar in 1994. Over two decades later the search

for exoplanets continues, with new discoveries coming in fast, offering tantalising possibilities for life beyond our Solar System. With all the stars that twinkle in the sky, think of how many planets are in orbit around them. Surely there should be another planet with life, even if it is in its simplest form – microbial life.

NASA's Kepler mission, now also referred to as 'K2' as it undergoes its secondary mission, has been spotting exoplanets in the night sky since 2009. At the time of writing the current tally for confirmed exoplanets sits at 2,652, with a further 2,737 potential candidates. Throughout the years astronomers have been able to make exciting discoveries from this dataset, introducing new planetary genres into the mix that include hot Jupiters, super-Earths, mini-Neptunes and, of course, water worlds. These planets are mainly characterised based on their radius, density and orbital parameters. If a planet is similar to the size and density of Jupiter, but closer to its host star than Jupiter is to the Sun, then it is normally characterised as a hot Jupiter. As for super-Earths, they are planets more massive than Earth but less massive than Uranus, which is around 14.5-times the mass of the Earth.

Zeng's current research focuses on the formation, evolution and chemistry of exoplanets

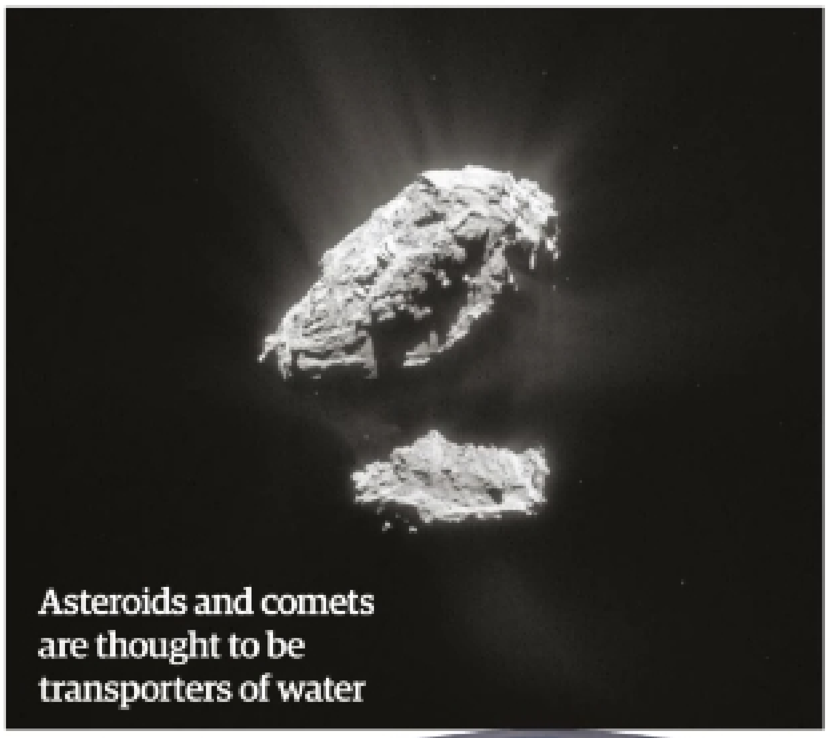
Although Kepler is currently reaching the end of its days as it is running out of fuel, its legacy will live on. It has been instrumental in discovering thousands of planets and, as of recently, even the possible detection of the first moon found outside our own Solar System. With this Kepler data, along with analyses from the star surveyor, Gaia, astronomers are getting a clearer picture of the composition and state of different stellar systems throughout the Milky Way. Gaia's main objective is to survey more than 1 billion stars in our galaxy, and its latest data release lists the three-dimensional positions and two-dimensional motions of over 1.3 billion stars, as well as their colour, surface termperatures, radii and brightnesses. By combining the two datasets astronomers have revealed the presence of more water worlds than anyone would have expected were out there. "It was a huge surprise to realise that there must be so many water worlds," says Dr Li Zeng, a Simons Collaboration on the Origins of Life postdoctoral fellow at Harvard University, Cambridge, Massachusetts.

At the Goldschmidt Conference, an internationally renowned conference held every year to present the latest advancements in many areas of science, held this year in August, Zeng announced that the galaxy is full of water worlds. However, there are more precise constraints to these planets than just 'a planet covered in water'. These exoplanets are, on average, two-and-a-half-times the radius and ten-times the mass of Earth. Anything less – in this instance one-and-a-half-times the radius and five-times the mass of Earth – are rocky planets, which resemble the inner four planets of our Solar System: Mercury, Venus, Earth and Mars. Anything above the water world constraints will most likely be a gas giant, which are planets similar to the outer Solar System planets – Jupiter, Saturn, Uranus and Neptune. "This reflects the cosmic element hierarchy of three major planet-building materials: rock, ice and gas," says Zeng. "Therefore, this natural ladder is reflected in planets. As you go from small to large planets you expect the correlation between the mass, or the size, of planets with their composition, and thus also with the cosmo-chemical sequence."

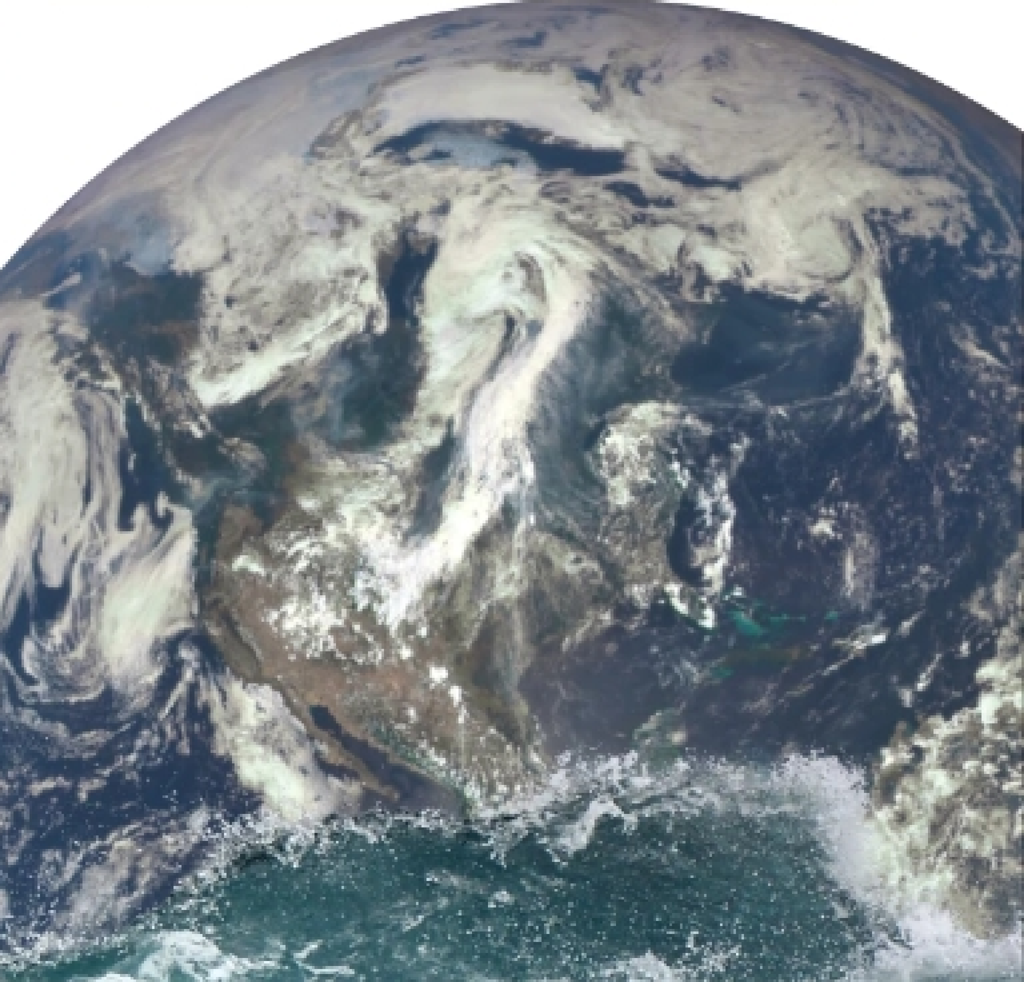
The new research claims that these planets could be made up of as much as 50 per cent water, which is significantly higher when compared to the Earth's mere 0.02 per cent by weight. However, Zeng is clear to point out that this is not water as we find it on Earth. "Their surface temperature is expected to be in the 200 to 500 degrees Celsius (392 to 932 degrees Fahrenheit) range. Their surface may be shrouded in a water-vapour-dominated atmosphere, with a liquid-water layer underneath.

> "Their surface may be shrouded in a water-vapour-dominated atmosphere, with a liquid-water layer underneath" **Dr Li Zeng**

ESA's Gaia spacecraft provides important information about the stars in our galaxy



Asteroids and comets are thought to be transporters of water

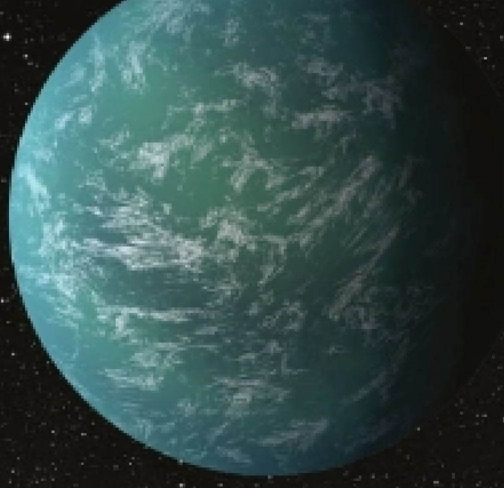


What makes up a water world?

Meet some of the most common planets spread throughout our galaxy

Rocky planets

On average these planets are 1.5-times the Earth's radius and are composed primarily of rocks or metals.



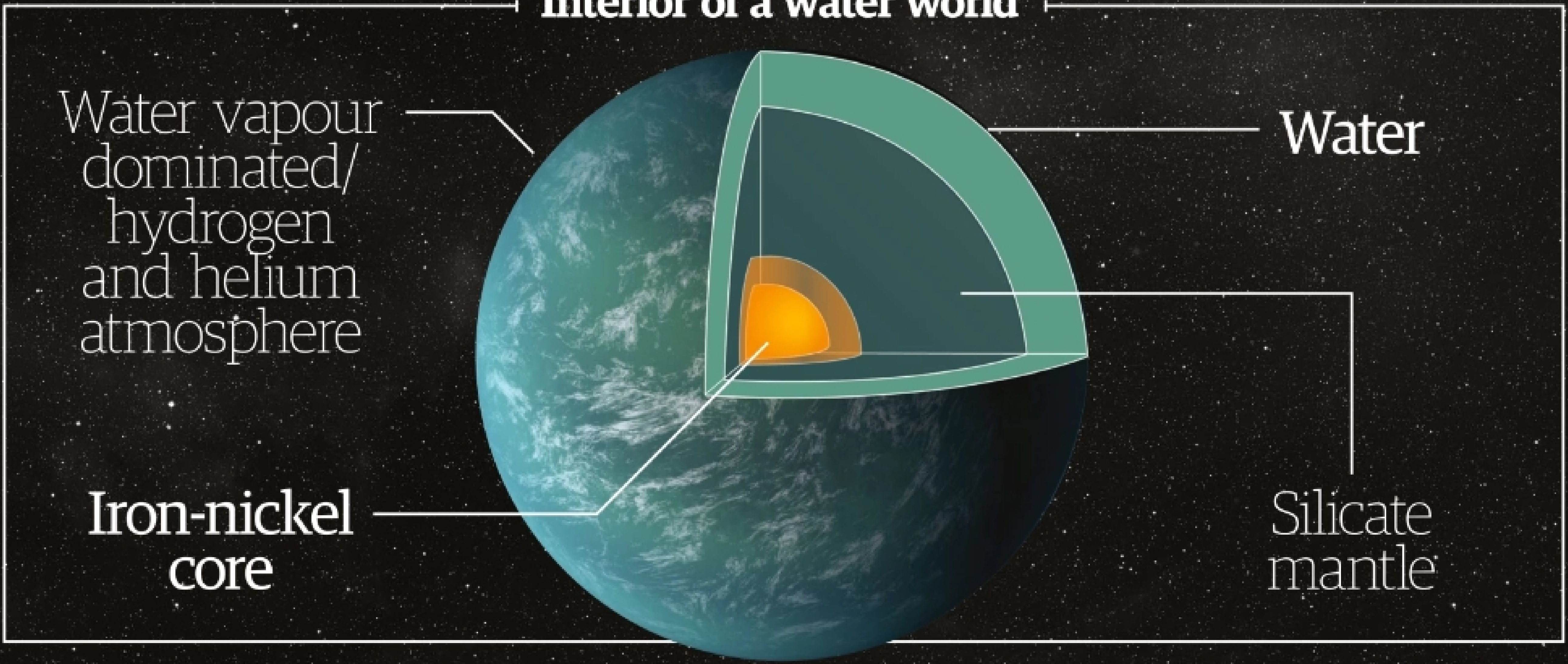
Water worlds

They are between two- and four-times the radius of Earth and contain large amounts of water.

Gas giants

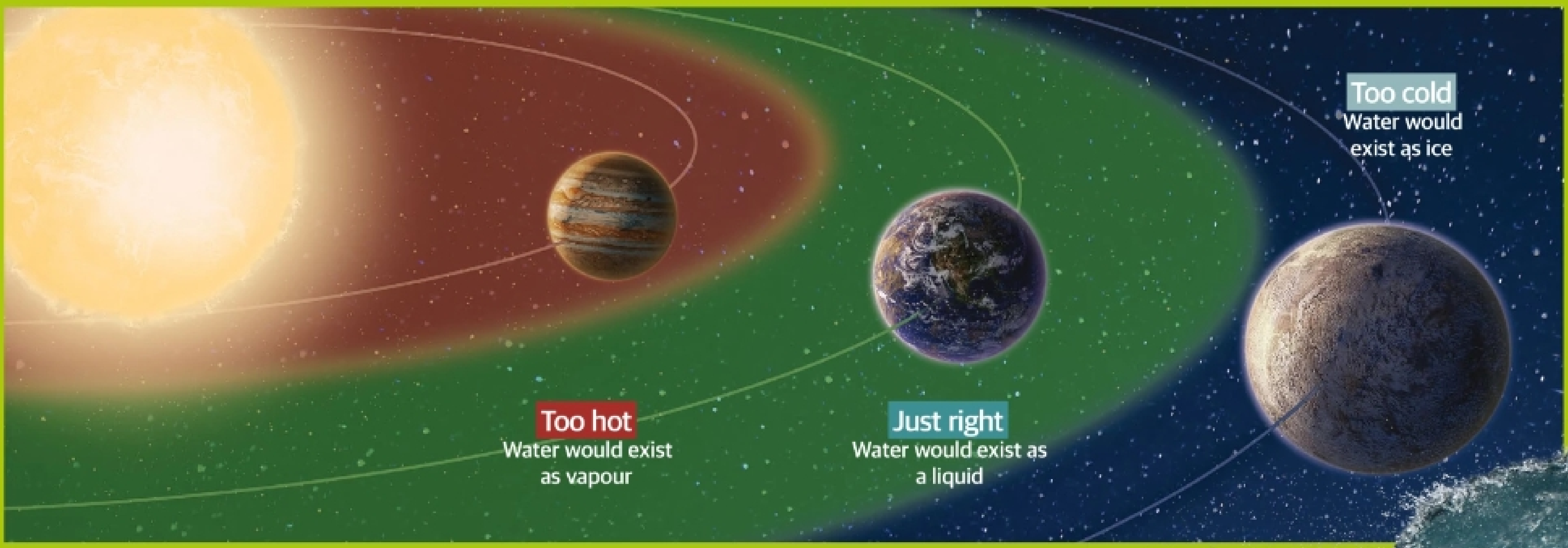
Much larger and much more massive planets are gas giants, composed primarily of hydrogen and helium with a small rocky core.

Interior of a water world



The habitable zone

The optimum distance from a star, where water could exist as a liquid



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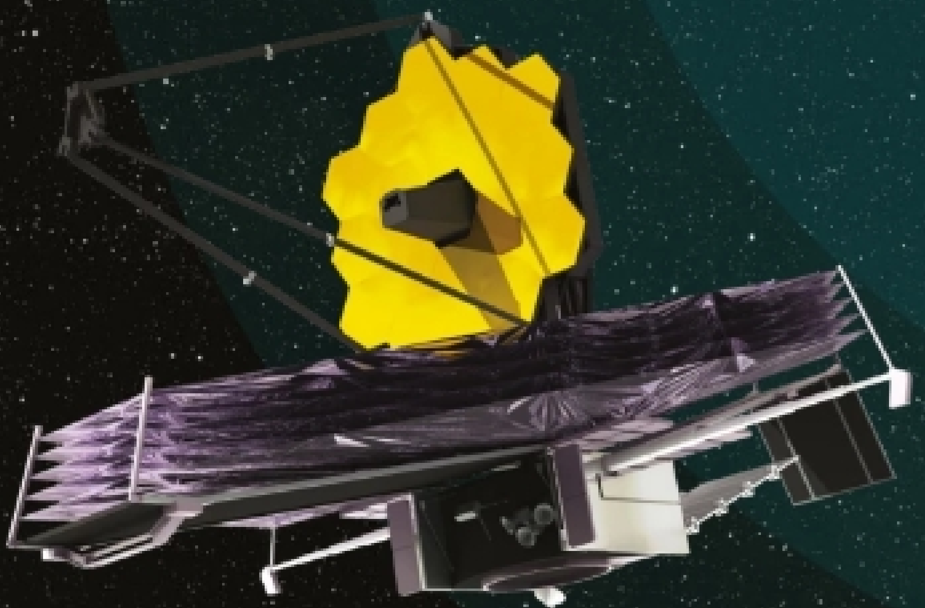
The future of exoplanet exploration

The pair will hunt down any exoplanets that could be hospitable for life, including water worlds



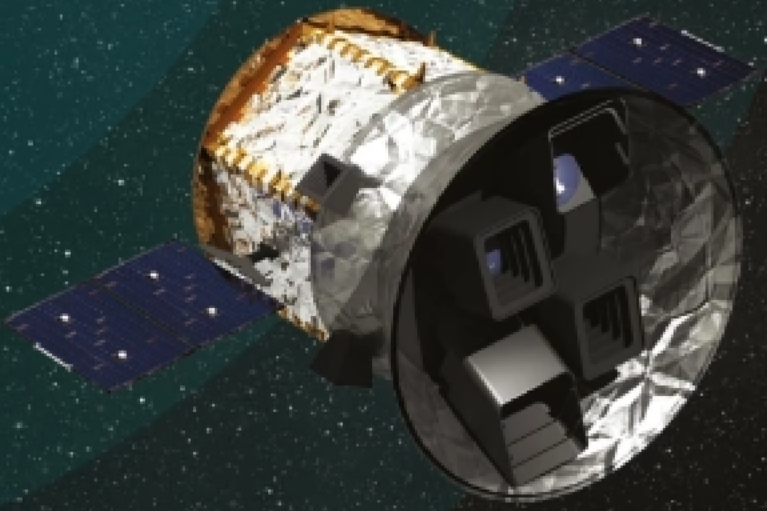
JWST

Transit spectroscopy

The NIRSpec (Near-Infrared Spectrograph) will be able to dissect the incoming light as an exoplanet passes in front of its host star. This will reveal the atmosphere's chemical composition, structure and temperature.

Coronagraph

Using the JWST's NIRCam (Near-Infrared Camera) coronagraph, exoplanets will be able to be directly imaged by blocking out the star's light. Although they will only appear as a dot, a lot can be learnt through spectroscopy.



TESS

Transit watchers

TESS is fitted with four CCDs that collectively create a 4,096 x 4,096-pixel detector. This is a masterpiece of exoplanet detection that will watch out for the transits of exoplanets, specifically Earth-like and super-Earth exoplanets.

Data handling

TESS' DHU (Data Handling Unit) does all the hard work; it is responsible for the hardware, software and firmware for data processing, storage, communications with the ground and spacecraft avionics.

Oxygen could join with hydrogen in nebulae in order to produce interstellar water

© NASA/ ESA; ESO; Adrian Mann; andrej67;

> "It's amazing to think that the enigmatic intermediate-size exoplanets could be water worlds" **Professor Sara Seager**

Moving deeper, one would expect to find this water transforms into high-pressure ices before we reach the solid rocky core," explains Zeng.

But it is not just the Kepler and Gaia data that made this result possible; a model developed by the Harvard team was also a big factor. This 'growth model' takes into account the formation and evolution of planets based on meteorite analysis and simulations of a protoplanetary disc. "The first direct constraint comes from our understanding of the chemistry of the Solar System, which comes from our understanding of meteorites in our own Solar System," says Zeng. "Secondly, all planets in the Solar System orbit near the same plane. This well-defined plane is the evidence that all planets formed within a disc surrounding the central host star." The most defining region in this model of the protoplanetary disc is the 'snow line'. This is the region where volatile compounds such as water, ammonia and methane are cold enough to freeze into ice, and this is thought to contribute heavily to the creation of the gas giants.

In the snow line rock and ice is thought to clump together, making up the cores of the gas giants we know today, before they are enveloped by hydrogen and helium. However, in the case of water worlds, they developed the rocky/icy core like the gas giants, but instead fell inward towards the host star and never developed their gaseous outer layers. So if anyone asks why we don't have any water worlds in our own Solar System, the short answer is that our system had a different evolution. Without the evolution of our Solar System panning out like it did, we never would of had life on Earth. But does that mean life is still able to evolve on exoplanets such as this with a different past?

Life is a complicated thing; there are many factors to take into account, and unfortunately modern science and technology just isn't good enough to be able to make a unambiguous detection of a world able to support life just yet. "A water world isn't just an Earth that we poured water on, it's a different planet and there's no reason to suppose the geology would be identical to ours," adds Elizabeth Tasker, an astronomer at the Japan

Natalie Batalha is an astrophysicist at the NASA Ames Research Center and the project scientist for NASA's Kepler mission

Aerospace Agency in Tokyo. "You really need to build up from basic physics and chemistry, rather than relying on Earth's analogy in order to tackle [complex] exoplanet problems."

What astronomers do know is that water is a necessity for life as we know it, and the universe is full of it. Hydrogen is the most abundant element in the universe and oxygen is third – with helium sitting in-between – and if you put both of those together you get water. "Whenever conditions are appropriate, such as on dust grain surfaces in cold nebulae, the oxygen atom will readily combine with the hydrogen atoms to form the water (H_2O) molecule," says Zeng. "Here we have found a population of exoplanets corresponding to these water worlds."

And still, there are many different factors to take into account when determining if life is possible in another system. For instance, there needs to be a manageable pressure, surface temperature and the right chemical composition allowing some sort of energy source. If one of these worlds resides within the star's habitable zone – the region surrounding the star where water can exist as a liquid – the temperatures possible high up in the atmosphere could be hospitable. Unfortunately this is all speculation until astronomers can intensely study the planets' atmospheres.

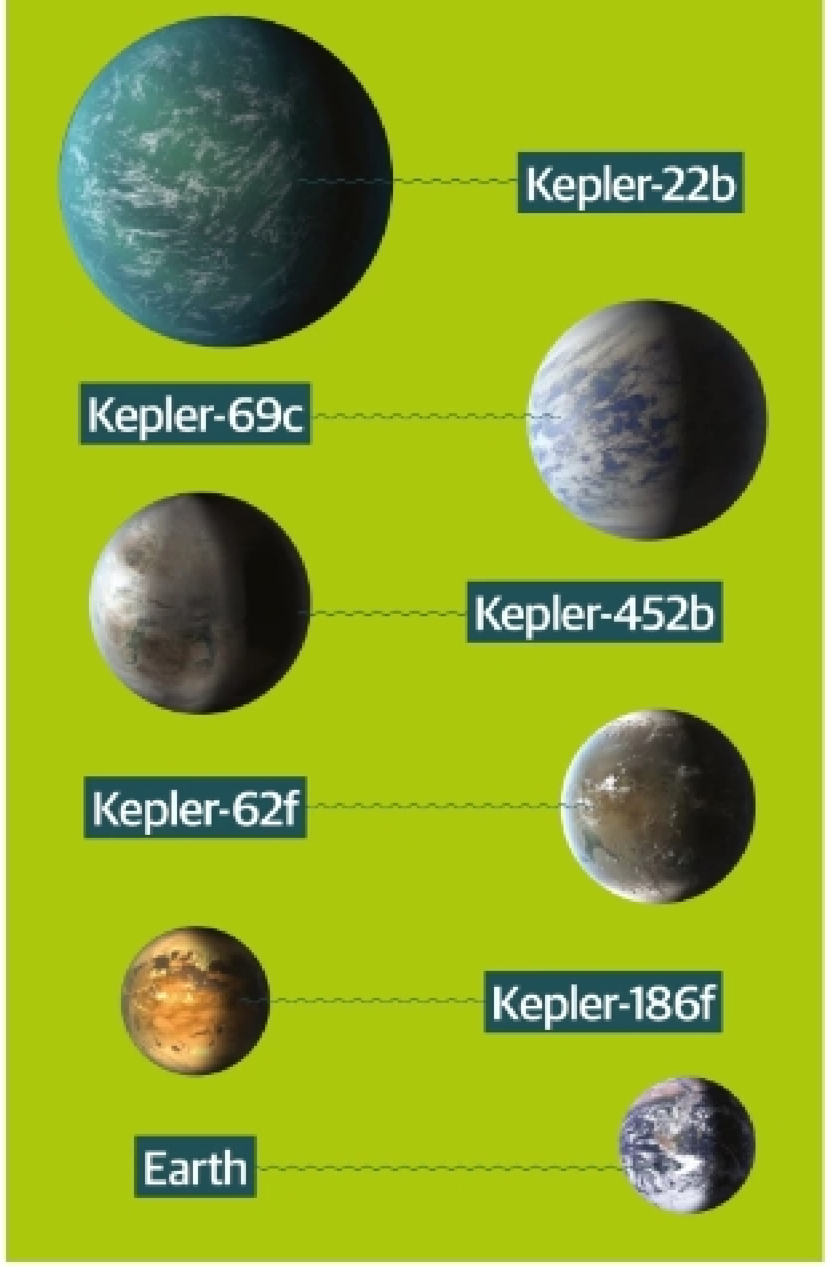
With the introduction of two space missions, NASA's James Webb Space Telescope (JWST), which is currently due to launch in 2021, and the already-launched Transiting Exoplanet Survey Satellite (TESS), the search for water worlds will intensify dramatically. TESS will provide in-depth analysis of Earth-sized and super-Earth worlds using its four top-quality CCD cameras. These cameras will watch out for the dimming of light from nearby stars, unveiling the presence of any exoplanets and revealing their physical parameters such as radius, mass and so on. "It's amazing to think that the enigmatic intermediate-size exoplanets could be water worlds with vast amounts of water. Hopefully atmosphere observations in the future – of thick steam atmospheres – can support or refute the new findings," says Professor Sara Seager, professor of planetary science at the Massachusetts Institute of Technology (MIT), United States, and deputy science director of the recently launched TESS mission, currently scouting the cosmos.

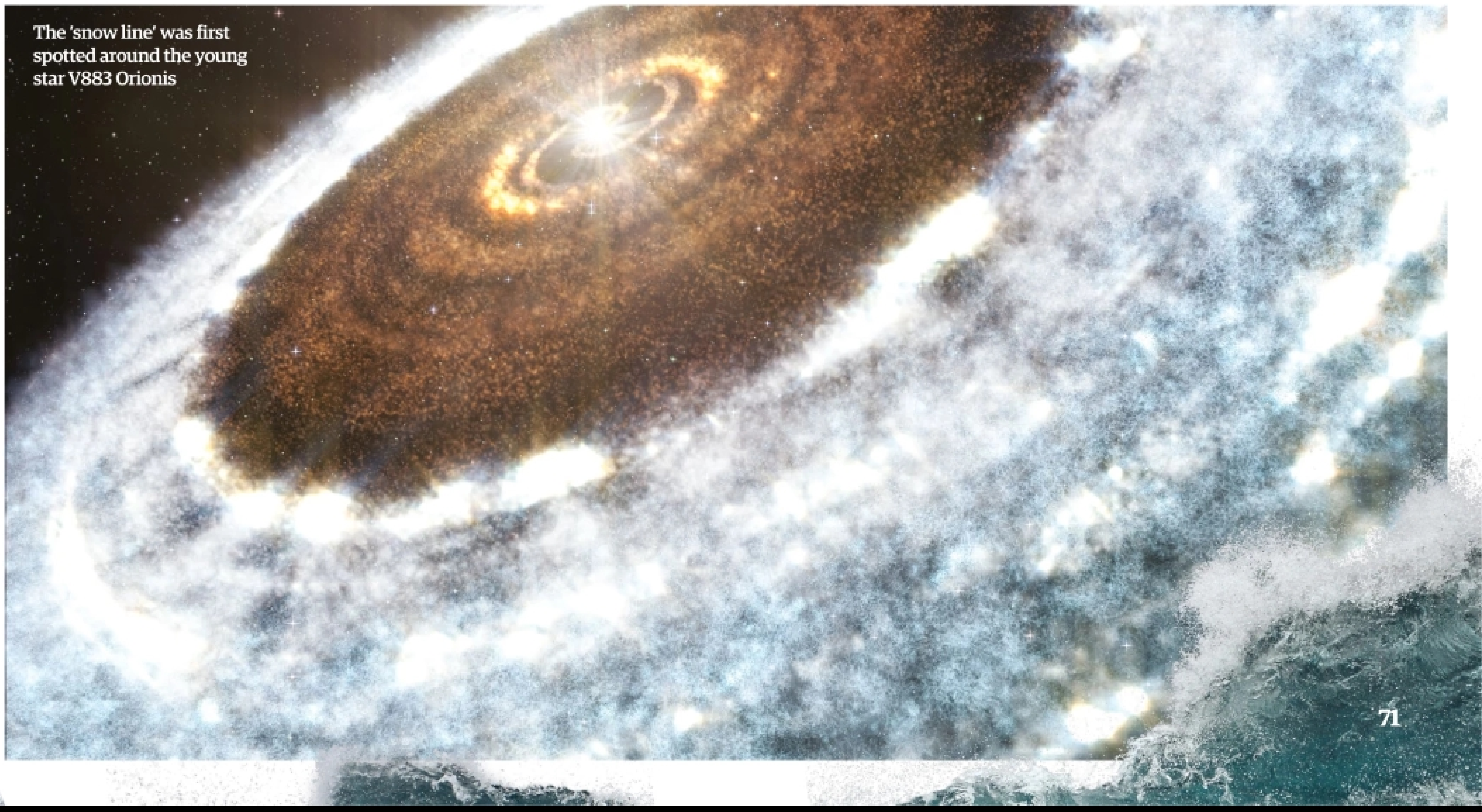
Such observations of exoplanets' atmospheres will come from the JWST and its incredible infrared capabilities. As starlight passes through the exoplanet and reaches the JWST its spectrometers will be able to detect molecules such as water, carbon dioxide and carbon monoxide in the atmosphere, painting a much clearer picture. "Our team's goal is to provide critical knowledge and insights to the astronomical community that will help to catalyse exoplanet research and make the best use of Webb in the limited time we have available," says Natalie Batalha of the NASA Ames Research Center, project scientist for Kepler and principal investigator to a project which will observe gas giants in early JWST operations.

With all of this to look forward to, the thought of water – and possibly even life – beyond the boundaries of our Solar System is becoming more and more exhilarating. With ever-improving technologies added to spacecraft, even more interesting discoveries are right around the corner.

Kepler's Earth-like exoplanets

These planets are the closest matches to Earth, but is it possible they could also be filled with water?





The 'snow line' was first spotted around the young star V883 Orionis

MYSTERIES OF THE UNIVERSE

MYSTERY OF THE SPACE

When scientists put their ear to the early universe, they found it yelled back - have we finally found the cause?

Reported by David Crookes

ROAR

In space nobody can hear you scream but, with the right equipment, it is possible to detect a roar. Indeed, that's what scientists discovered back in 2006 when they began to look to the dawn of the universe using seven precision radiometers fixed to a machine that was sent to space on a huge balloon. It was able to pick up radio waves from the heat of distant stars, but what came through that year was nothing short of astounding.

As the machine listened from a height of about 37 kilometres (23 miles), it picked up a signal that was six-times greater than expected by cosmologists. Too loud to be early stars and far greater than the predicted combined radio emission from distant galaxies, it caused great puzzlement. Yet scientists still don't know what is causing it. What's more, it could even hamper efforts to search for signals from the first stars to form after the Big Bang.

To understand what's going on, it's important to establish some facts. First of all, the instrument that was sent into space that year was the Absolute Radiometer for Cosmology, Astrophysics, and Diffuse Emission (ARCADE), and it was built to extend the study of the cosmic microwave background spectrum at lower frequencies.

Its science goals - as it floated high above Earth's atmosphere, free of interference from our planet - were to find heat from the first generation of stars, search for particle physics relics from the Big Bang and observe the formation of structure from the first stars and galaxies. It did so by scanning seven per cent of the night sky looking for radio signals, since distant light becomes radio waves as it loses energy over distance.

In this sense ARCADE was able to make 'absolutely calibrated zero-level' measurements, which means it was measuring the actual brightness of something in real physical terms rather than whether an object was brighter relative to another. This was different to typical radio telescopes which observe and contrast two points in the sky. By looking at all of the 'light' and comparing it to a blackbody source, ARCADE was able to see the combination of many dim sources. It was then the intensity of one particular signal became apparent, albeit over many months.

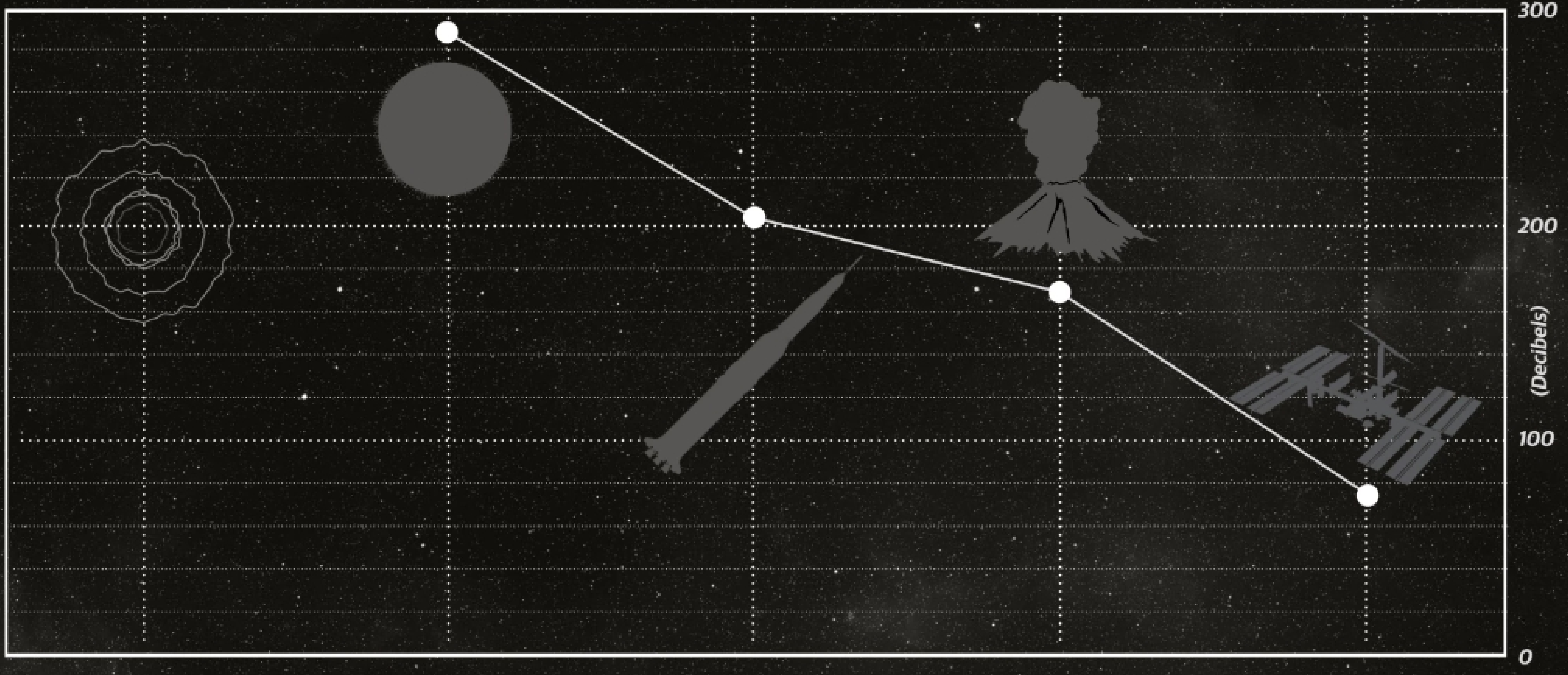
"While it might make a good movie to see us surprised when we see the light meter pop over to a value six-times what was expected, we actually spent years getting ready for our balloon flight and a very busy night taking data," says NASA scientist Dale J. Fixsen. "It then took months of data analysis to first separate instrumental effects from the signal and then to separate galactic radiation from the signal. So the surprise was gradually revealed over months." That said, the impact was still huge.

Since then scientists have looked to see where the radiation is coming from while looking to establish the properties of the signal. The latter

The space roar is caused by synchrotron radiation which is created when atomic particles spiral around magnetic field lines

Sound comparisons in the universe

Listen up: space could be a noisy place if it was full of air



Space roar
Six-times intensity of any source measured
The space roar has been found to be much louder than most parts of the universe.

The Sun
290 decibels
If we could hear the Sun, we'd all be wearing earmuffs. Even from Earth the Sun would be 125 decibels.

Saturn V rocket
204 decibels
If you were standing too close when a rocket launched, the constant sound would seriously hurt your ears.

A big caldera
172 decibels
Krakatau made an incredible sound when it erupted on 27 August 1883; it was heard 100 miles away.

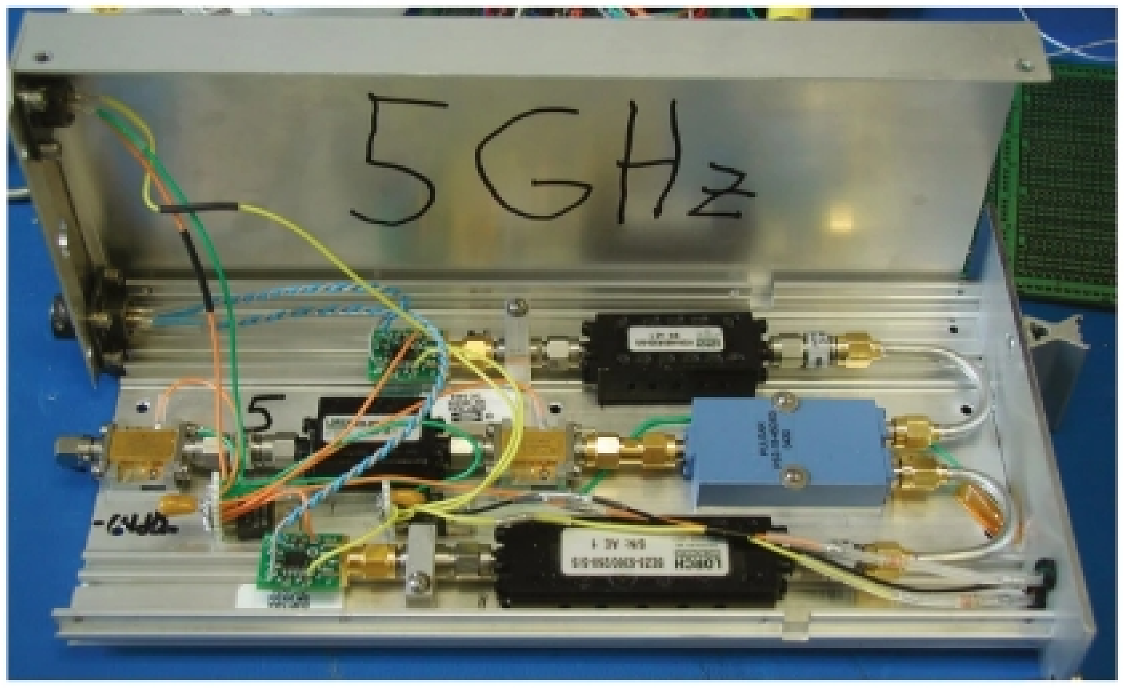
ISS
78 decibels
ISS astronauts used to wear earplugs all day, but NASA worked on lowering noise levels.

became apparent rather quickly. "It's a diffuse signal coming from all directions, so it is not caused by any one single object," explains Al Kogut, who headed the ARCADE team at NASA's Goddard Space Flight Center in Greenbelt, Maryland. "The signal also has a frequency spectrum, or 'colour', that is similar to radio emission from our own Milky Way galaxy."

Scientists call the signal 'radio synchrotron background' - background being an emission from many individual sources and blending together into a diffuse glow. But because the 'space roar' is caused by synchrotron radiation, a type of emission from high-energy charged particles in magnetic fields, and since every source has the same characteristic spectrum, pinpointing the origin of this intense signal is difficult.

"It has been known since the late-1960s that the combined radio emission from distant galaxies should form a diffuse radio background coming from all directions," explains Kogut. "The space roar is similar to this expected signal, but there doesn't seem to be six-times more galaxies in the distant universe to make up the difference, which could point to something new and exciting as the source."

Whether or not this source is inside or outside the Milky Way has been debated. "There are good arguments why it cannot be coming from within the Milky Way galaxy, and good arguments for



Above: This is the 5 GHz radiometer back end, which splits into two frequency subchannels

Left: Getting ready for the launch of the ARCADE module, which peered back to the dawn of the universe

What do the results say?

What scientists know about the mysterious roar

> "If it is from a halo around our galaxy, it would make the Milky Way a weird galaxy"

NASA's Dale J. Fixsen says the Milky Way looks like a normal spiral galaxy, so it would be unusual if the roar was found to come from a source connected with it.

> "The determination of the level of the radio background was not solely based on ARCADE"

Jack Singal, assistant professor of physics at the University of Richmond, says other measurements at lower frequencies have previously hinted at such radio background, going back to the 1960s.

> "Current data shows the problem, but doesn't really point to a solution"

Al Kogut, who headed the ARCADE team, says projects such as the 91-metre (300-foot) radio telescope at Green Bank will help resolve the issue.

why it cannot be coming from outside the galaxy," Kogut tells us. One of those which falls into the former is that it doesn't seem to follow the spatial distribution of Milky Way radio emission, but nobody is saying for certain that it isn't from a source closer to home, only that the smart money is on it coming from elsewhere.

"I wouldn't quite say that scientists have largely ruled out the possibility of the radio synchrotron background originating from our galaxy," says Jack Singal, assistant professor of physics at the University of Richmond, who recently led a workshop on the matter. "However I would say that this explanation does seem to be less likely.

"The primary reason is that it would make our galaxy completely unlike any similar spiral galaxy, which as far as we can tell do not exhibit the sort of giant, spherical, radio-emitting halo extending far beyond the galactic disc that would be required. There are other issues as well, such as that it would require a complete rethinking of our models of the galactic magnetic field."

Fixsen agrees wholeheartedly with this. "In other spiral galaxies there is a close relation between the infrared and radio emission, even in small sections of these others. So if it is from a halo around our galaxy it would make the Milky Way a weird galaxy, while in most other respects it seems like a 'normal' spiral galaxy," he tells us.

This would by default point to an excess signal that is primarily extragalactic in origin. "It would make it the most interesting photon background in the sky at the moment because the source population is completely unknown," Singal says. But since the universe is so vast this doesn't exactly narrow things down that much, which is why scientists have been working hard to come up with multiple theories.

Some ideas are hard to get your head around. American physicist David Brown, for example, says the space roar could be "the first great empirical success of M-theory", a broad mathematical framework encompassing string theory. "There might be a Fredkin-Wolfram automaton spread across multitudes of alternate universes, yielding recurrent physical time with endless repetitions of all possible physical events," he wrote on a blog. What this supposes is the early universe had much more real matter than today, accounting for the powerful radio signal.

But if that is too far out, then there are other theories to get your teeth into. "Radio astronomers have looked at the sky and have identified a couple of types of synchrotron sources," Fixsen says. "These have distributions that can be extrapolated so we can account for the full distributions."

He explains that synchrotron radiation is easy to make. "All you need is energetic particles and a magnetic field, and there are energetic particles everywhere, produced by supernovae, stellar winds, black holes, even OB stars," he says. "Intergalactic

"What this supposes is the early universe had much more real matter than today, accounting for the powerful radio signal"

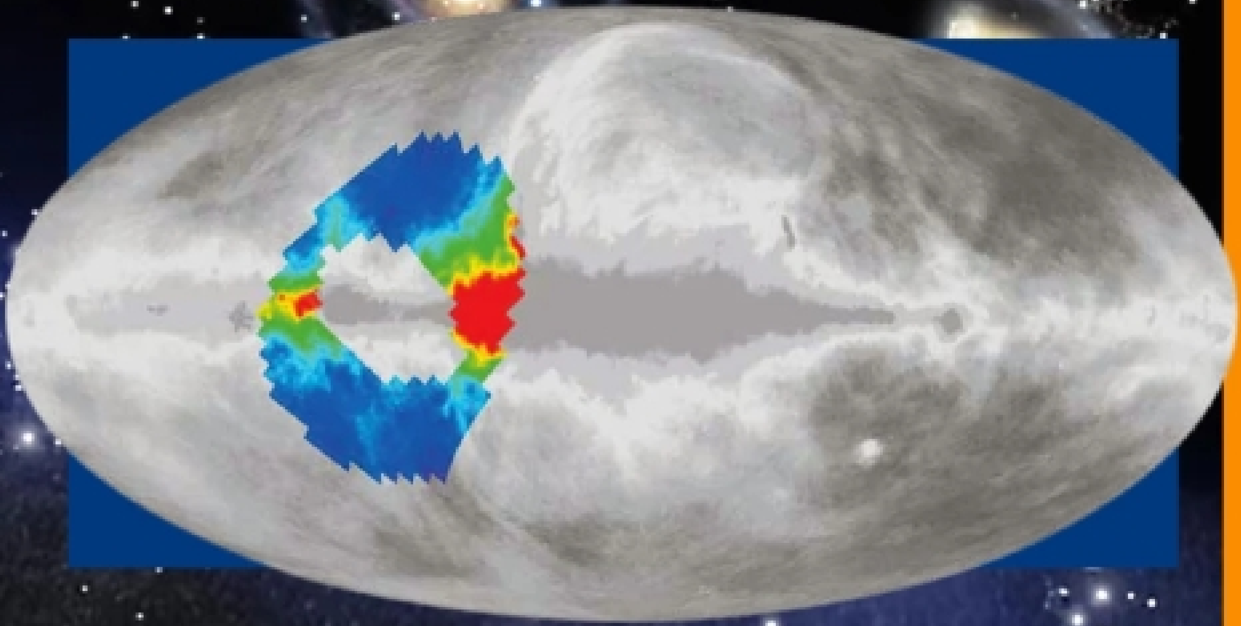
Above: Jack Singal, assistant professor of physics at the University of Richmond, tapes down heaters on ARCADE 2

Below: The giant balloon is being filled prior to its launch, and stands upright

© NASA; Adrian Mann

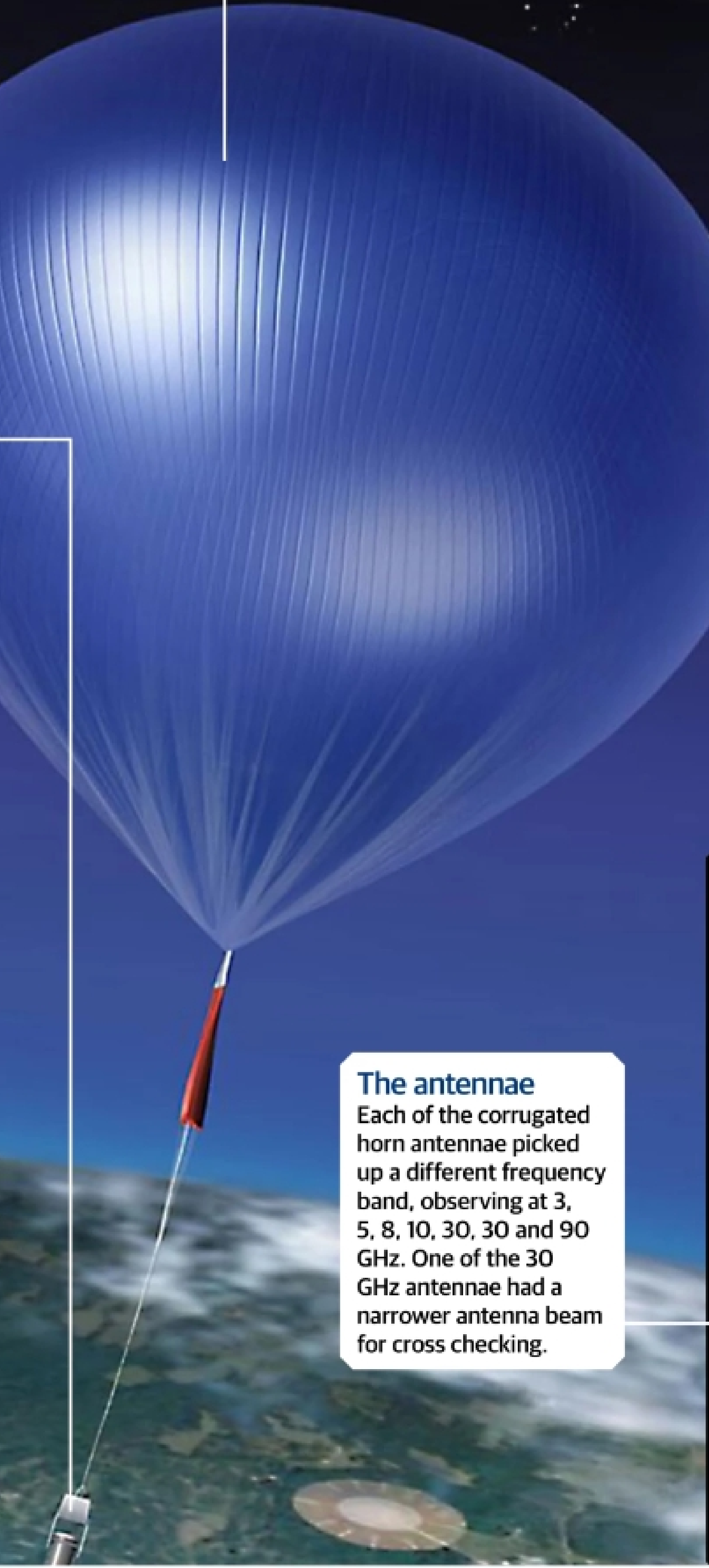
ARCADE

How a balloon was able to detect the space roar



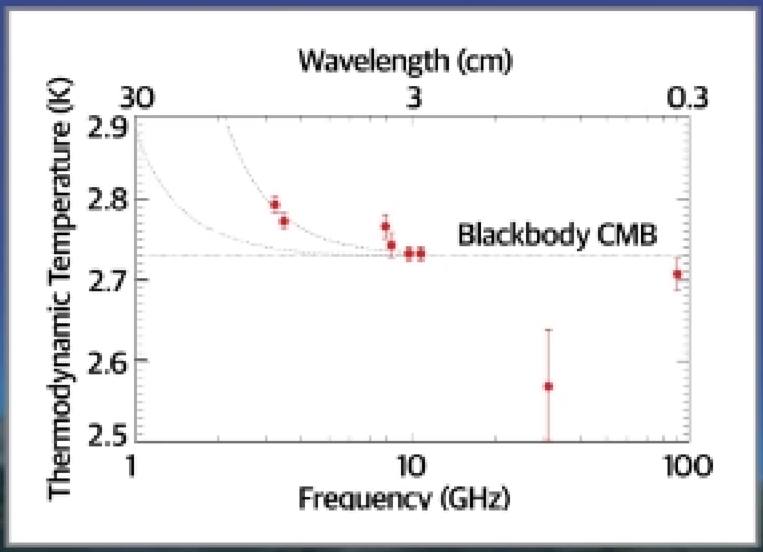
The balloon
This giant helium balloon was tethered to ARCADE, allowing the payload to be carried to an altitude of 37 kilometres (23 miles), from where it had an unobstructed view into space.

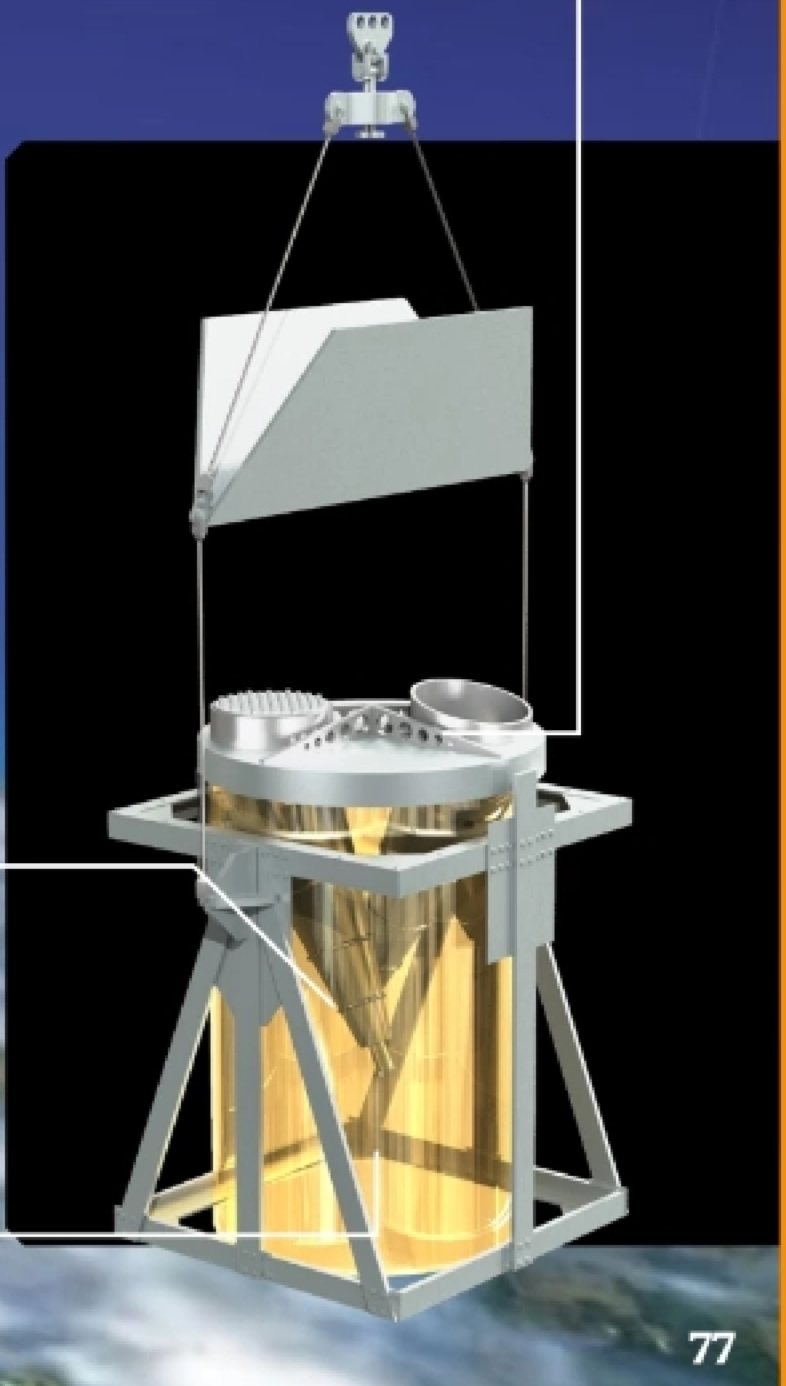
Seven radiometers
Soaked in liquid helium, the seven radiometers were placed towards the top of the vacuum flask. They measured the frequency spectrum of the Cosmic Microwave Background at centimetre wavelengths.



Reflective shield
The reflective shield which sat above the vacuum flask ensured the antennae did not have a view of the flight train and the parachute.

Sky-observing aperture
The carousel had a porthole for sky viewing. During its observations ARCADE was able to view about seven per cent of the night sky.



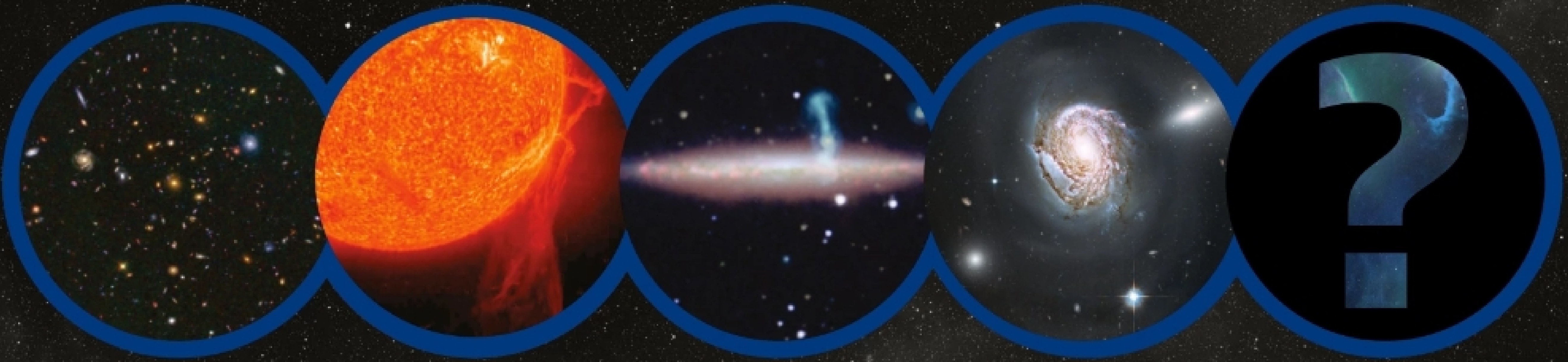


The antennae
Each of the corrugated horn antennae picked up a different frequency band, observing at 3, 5, 8, 10, 30, 30 and 90 GHz. One of the 30 GHz antennae had a narrower antenna beam for cross checking.

Liquid helium
Since the instruments needed to measure tiny differences in temperature from the very first stars, it was important that ARCADE was as cool as possible. Liquid helium cooled the payload to -270°C (-454°F).

What it's thought to be

Numerous theories about the space roar have been raised



The earliest stars

ARCADE was designed to detect the faintest signs of heat from the first generation of stars, so do these account for the noise? It's unlikely since it was six-times louder than expected – far greater than what those stars should be emitting.

A bubble around the Sun

It's possible that there is a small bubble around the Sun. As scientist Dale J. Fixsen tells us, it wouldn't have to be very bright since it is so close to us, thereby appearing normal.

Dim radio galaxies packed together

There is one major problem with the theory that the source is radio galaxies very close together: those galaxies would have to be so packed that they'd effectively merge into one.

Gases swirling around galaxy clusters

Maybe radiation is being emitted from the gases of large galaxy clusters, but the main issue here is that the instruments used by ARCADE are unlikely to have picked them up.

An unknown source

The most likely explanation is that there is something out there that we just haven't yet discovered, and that is why the 'space roar' is so exciting. The only way we'll discover the root cause is with further investigation.

space seems to be filled with very hot gas, so if intergalactic magnetic fields were strong enough [stronger than predicted], they could generate smooth synchrotron radiation."

It is also known that synchrotron radiation is associated with star production. "This also generates infrared radiation, hence the close correlation," Fixsen continues. "But perhaps the first stars generated synchrotron radiation yet, before metals were produced, they did not generate very much infrared radiation. Or perhaps there is some process that we haven't thought of yet."

So what does this leave us with? "Possible sources include either diffuse large-scale mechanisms such as turbulently merging clusters of galaxies, or an entirely new class of heretofore unknown incredibly numerous individual sources of radio emission in the universe," Singal tells us. "But anything in that regard is highly speculative at the moment, and some suggestions that have been raised include annihilating dark matter, supernovae of the first generations of stars and many others."

Indeed, some scientists have suggested gases in large clusters of galaxies could be the source, although it's unlikely ARCADE's instruments would have been able to detect radiation from any of them. Similarly, there is a chance that the signal was detected from the earliest stars or that it is originating from lots of otherwise dim radio galaxies, the accumulative effect of which is being picked up. But if this was the case then they'd have to be packed incredibly tightly, to the point that there is no gap between them. In reality this appears unlikely.

"Of course there is also the possibility that there has been a coincidence of errors among ARCADE and the other measurements to date that have mismeasured the level of the radio synchrotron background," says Singal. "This does seem unlikely given that these are very different instruments measuring in quite different frequency bands."

Whatever the signal is, it's also causing a knock-on effect. As NASA has pointed out in the past, the earliest stars are hidden behind the space roar, and that is making them more difficult to detect. It is as if science is giving with one hand and taking with another, but to have uncovered something so unusual is immensely exciting. When you're ruling out an origin from primordial stars and known radio sources such as gas in the outermost

NASA; JPL-Caltech; ESO;

Above left: Was there more real matter in the very early universe, accounting for a louder noise when seeking to monitor those fledgling moments?

Left: NASA scientist Dale J. Fixsen (right) works with Ed Wollack (left)

Above: Such is the 'noise' from the space roar, astronomers fear not being able to monitor the earliest of stars following the Big Bang

> "I think we may need some brilliant new origin hypothesis that nobody has thought of yet" **Dr Jack Singal**

halo of our galaxy, it's a mystery any scientist would savour with relish.

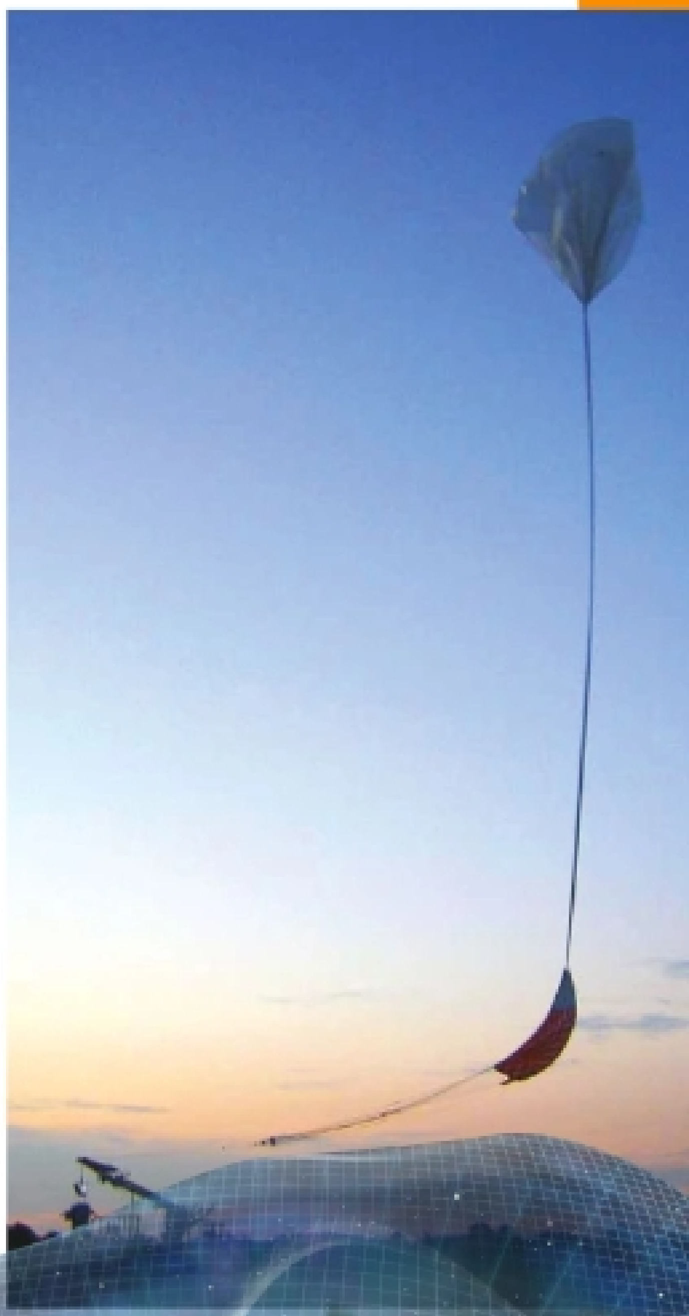
In order for scientists to finally resolve this 13-year conundrum, more research and evidence is sorely needed. As it stands there is a debate over sending ARCADE back up, and given its precise set of instruments, immersed in more than 500 gallons of ultra-cold liquid helium to make them even more sensitive, there would certainly be no harm in doing so.

But there are also new projects emerging which could help. "One of them will use the 91-metre (300-foot) radio telescope at Green Bank, West Virginia, to map the radio sky to higher precision than before," says Kogut. "Perhaps this will shed some light on the mystery."

Singal certainly hopes so. He is working on the Green Bank Telescope project, making use of the largest clear-aperture radio telescope in the world to measure the level of the background as a primary, rather than ancillary goal. It will do this using a definitive, purpose-built, absolutely calibrated zero-level measurement taken at the MHz frequencies where the radio sky is brightest.

"This measurement is currently being developed by a team which I am on, utilising custom instrumentation which will be mounted on the telescope," he tells us. There is also going to be another measurement attempt, this one looking to measure or further limit the so-called 'anisotropy' of the radio synchrotron background, again at the MHz frequencies where it dominates.

"That is not its absolute level, but rather the small differences from place to place in the sky," Singal says. "With some collaborators I am trying a first attempt at that using the Low-Frequency Array [LOFAR] in The Netherlands. Both of these measurements in concert can help nail down whether the radio synchrotron background is primarily galactic or extragalactic in origin. Beyond that, I think we may need some brilliant new origin hypothesis that nobody has thought of yet."



Right: ARCADE was launched on a large balloon in 2006

DOES SPACE HAVE A FINAL DIMENSION?

There could be more to the universe than meets the eye with extra facets beyond space and time

— Reported by Colin Stuart —

© Tobias Roetsch

"Curiouser and curiouser!" cried Alice. In Lewis Carroll's surreal Victorian story the eponymous character goes on adventures in Wonderland. There she meets a cast of quirky characters in a world that's so alien it defies belief and common sense. To reach this otherworldly place she disappears down a rabbit hole and into another dimension.

As wonderful and wacky as *Alice in Wonderland* is, some physicists believe something similar might be at play in our universe. "It all starts with the hierarchy problem," says Kris Pardo from the Department of Astrophysical Sciences at Princeton University. Gravity, it seems, doesn't play by the rules, particularly when you compare it to the other major forces. "It's just so much weaker," says Pardo. It's ten thousand trillion trillion trillion-times feebler than the strong nuclear force that helps bind atomic nuclei together, for example. To see just how weak gravity really is, remember that you can jump into the air and temporarily overcome the collective gravitational pull of six trillion trillion kilograms of the Earth beneath your feet.

The puzzle of why gravity is so puny compared to its sibling forces is one of the greatest mysteries in physics. It has led some researchers to suggest that gravity must do the astronomical equivalent of Alice and disappear down a celestial rabbit hole. What if gravity isn't really weaker – we only perceive it that way because it leaks into additional dimensions? If you could be an all-seeing eye, capable of observing every dimension at once, you wouldn't encounter a hierarchy problem at all. Such an idea might sound far-fetched but, thanks to recent breakthroughs, Pardo has been able to test it.

Gravity may disappear into extra dimensions, just as Alice disappeared down the rabbit hole in *Alice in Wonderland*

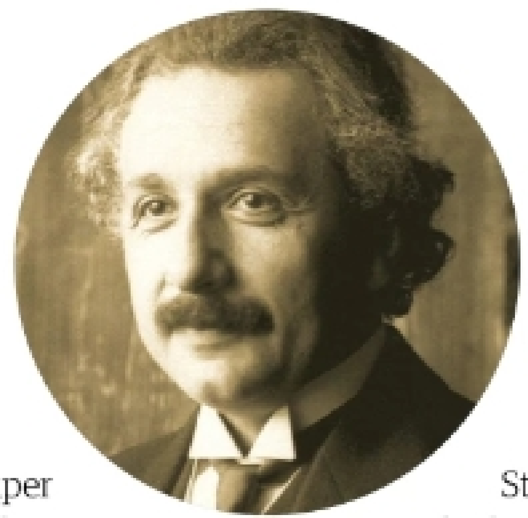
In 2015, physicists detected gravitational waves for the first time. These ripples in the very fabric of space were predicted by Albert Einstein 100 years earlier. Calamitous events in the universe send out rolling waves, much like those created when a stone is dropped into a pond. When the waves pass through the Earth they can be detected by experiments like the Laser Interferometer Gravitational-Wave Observatory (LIGO) in the US. Its four-kilometre (2.5-mile) arms are sensitive to changes in space equivalent to one-ten-thousandth the width of a proton. The discovery was so monumental that the Nobel Prize in Physics was awarded to the founders of the facility in 2017.

The first gravitational waves detected by LIGO came from the collision of two black holes about 1.3 billion light years away. But in August 2017 another type of collision was picked up: two neutron stars smashing together 130 million light years away. This event – known as GW170817 after the date it was first detected – presented a unique opportunity to test the idea of gravity leaking into extra dimensions. That's because a neutron star merger produces a searing flash of light in the form of gamma rays along with the gravitational waves. Black holes, on the other hand, famously gobble up light. So GW170817 became the first event ever detected to emit both light and gravitational waves.

Pardo and his colleagues were able to compare the flash of gamma rays with the gravitational waves. "We think we know how much energy is released in the form of gravitational waves after an event like the one that we saw," Pardo says. "And we think we know how much of that energy is going to be lost as the wave travels from the source to us." The light from the collision also fades as it makes its way here. If you know how much energy was released, and how much energy you detect once it reaches Earth, you can work backwards to figure out how far away the collision occurred. The more it has faded, the further it has travelled across space to get here. Crucially, a neutron star merger allows you to compare two independent measures of distance – light and gravitational waves – in a way that a black hole merger cannot.

If gravity really is leaking into extra dimensions then some of the gravitational wave energy will seep into them en route to Earth. Light doesn't leak, so the two measures would disagree on the distance travelled. "It would seem like the gravitational waves were coming from further away," says Pardo. Back in July 2018, Pardo and his colleagues released a scientific paper with their findings. "The gravitational waves weakened in the way we expected," he says. In other words, he found no evidence of gravity leaking into other dimensions.

It sounds like a hammer blow, but Pardo adds an important caveat: "There are some theories of extra dimensions that you can't probe with the large scales that we worked with," he says. "To test ideas like string theory, that have very small extra dimensions, you need to be looking at much higher energy events than the ones we looked at."



Albert Einstein predicted the existence of gravitational waves in his 1915 General Theory of Relativity

String theory is notorious and probably the best known example of a theory that invokes the presence of extra dimensions. It also has its origins in the study of gravity. Physicists would love to combine Einstein's General Theory of Relativity – the theory of gravity that predicted the existence of gravitational waves in the first place – with quantum physics, which describes interactions in the sub-atomic world. Except these two theories stubbornly refuse to play nicely together. Attempts to combine them lead to discrepancies even more absurd than the weird world described in the pages of *Alice in Wonderland*. For example, the probabilities of some events happening turns out to be more certain than certain – a sure sign something is wrong. String theorists attempt to get around this problem by invoking the presence of extra dimensions. Add them in and the maths works beautifully.

> "If gravity really is leaking into extra dimensions then some of the gravitational wave energy will seep into them"

Dimensions of the universe

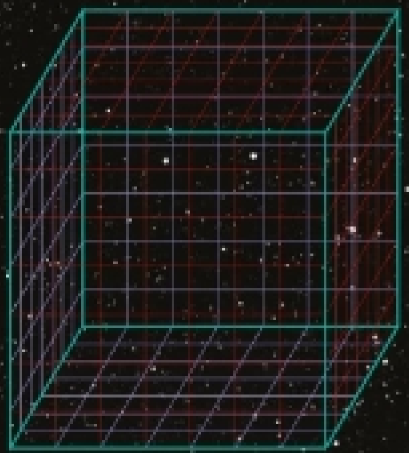
How do they differ from the ones we can observe?

First dimension

The first dimension is often thought of as a line – an object's position within one-dimensional space can be described by a single measurement. However, a single dimension need not necessarily be limited to straight lines – it may encompass a position on a circle such as compass points, or azimuth in the night sky.

Second dimension

A two-dimensional object is described by two separate measurements – the simplest example is a flat plane in which any position can be defined on a grid of x and y coordinates that are at right angles to each other. However, there are many other objects, such as spherical and cylindrical surfaces, that are also two dimensional.



Third dimension

The space we perceive in everyday life is three dimensional – we can define the position of any object within it by a set of three numbers, such as x, y and z coordinates at right angles to one another, or a set of celestial coordinates plus a distance from Earth. However, our perception is far from the whole story.

Seventh dimension

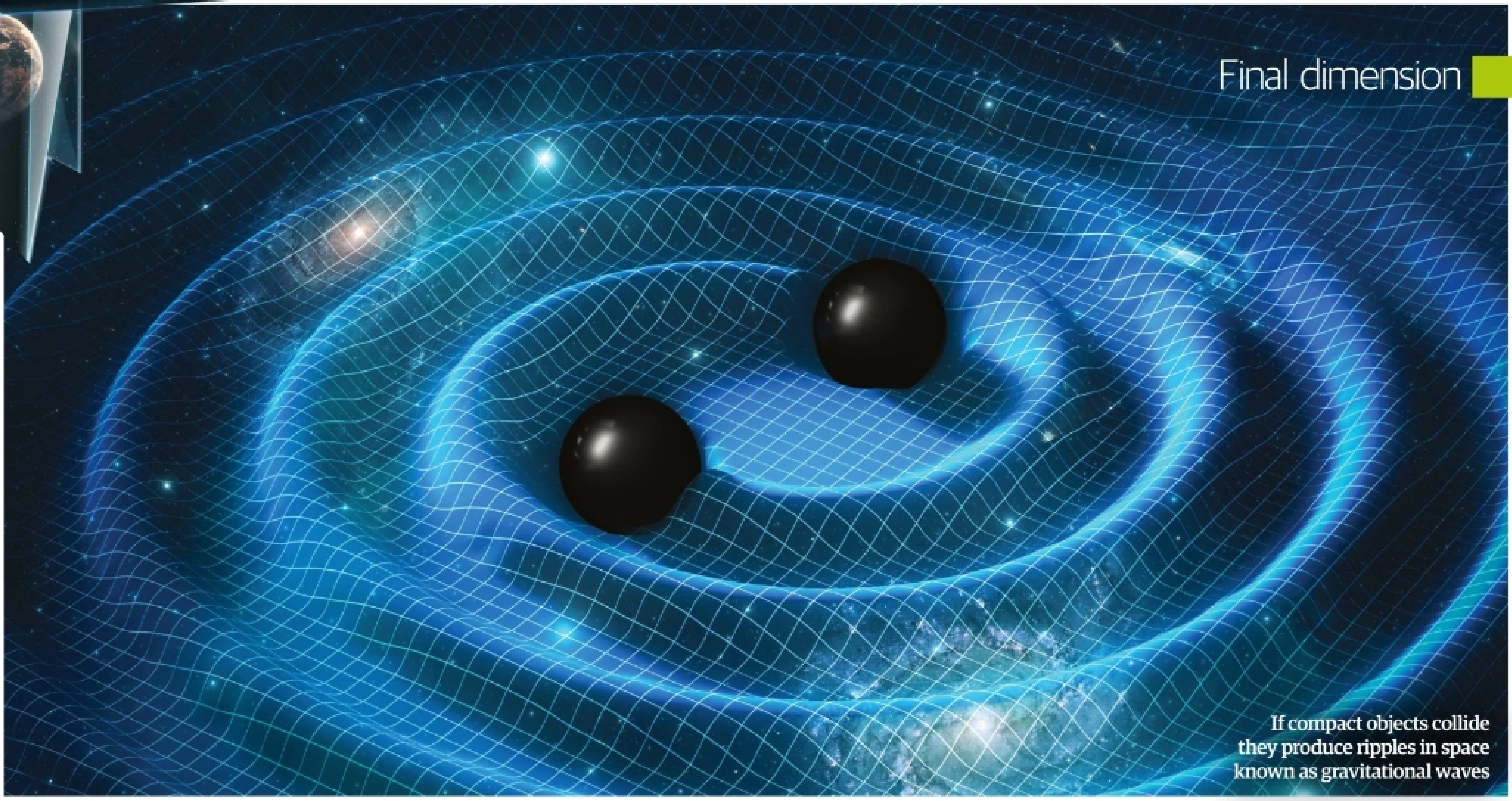
In the seventh dimension, and unlike the sixth dimension, possible worlds are born out of various starting conditions. What's more, everything is different from the very beginning of time.

Eighth dimension

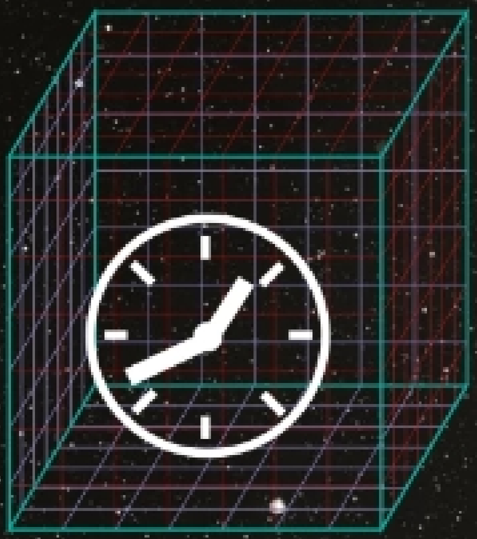
Just like the seventh dimension, the eighth presents a plane of possible histories of the universe, each of which begin with a variety of starting conditions – all of which branch out infinitely.

Ninth dimension

It's not just all of the possible histories of the universe that are different in the ninth dimension – the laws that we understand to govern the cosmos also vary.



If compact objects collide they produce ripples in space known as gravitational waves



Fourth dimension

So far as we know, movement along the time dimension happens in a single direction and we can never revisit the past. Just as importantly, the dimensions of time and space are bound together in a four-dimensional continuum that allows each to vary in extreme conditions, as described by Einstein's theories of relativity.

Fifth dimension

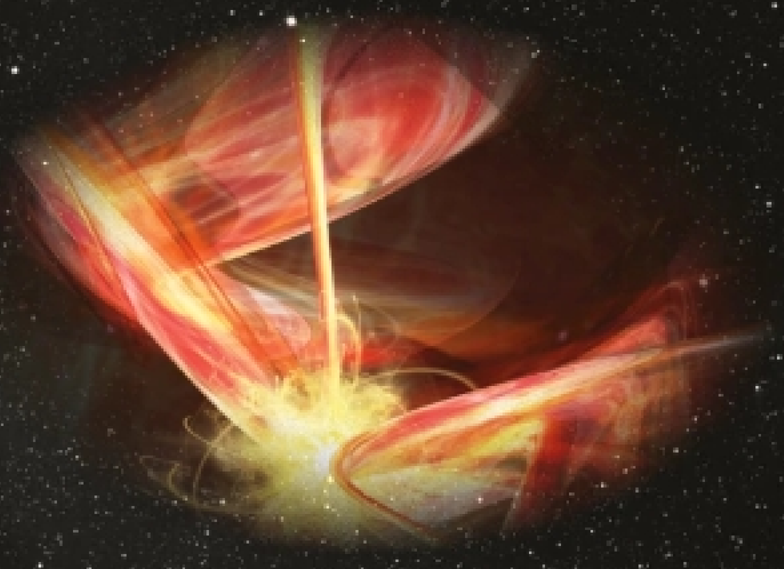
In this dimension you'll find another world that's slightly different to ours – we could measure similarities and differences to our own planet. A fifth dimension with similar properties to those of the three known space dimensions would be capable of giving rise to objects with four space dimensions, such as the well-known tesseract.

Sixth dimension

All possible worlds and universes start in the same way. You could easily travel backwards in time or go to different futures. If superstring theory is correct, then a linear fourth dimension of space perpendicular to the others does not exist, but there are at least six higher dimensions in which superstrings can oscillate.

Tenth dimension

Superstring theory combines string theory and supersymmetry. It manages to escape mathematical inconsistencies when combining gravity and quantum physics, but only by invoking a total of ten dimensions.
It suggests that particles are made of tiny vibrating strings that resonate across dimensions.



11th dimension

There are five different versions of superstring theory, but M-theory attempts to combine them into just one model. In M-theory the five superstring theories form a membrane which provides an extra dimension, hence why M-theory has 11 dimensions to superstring theory's ten.

26th dimension

Bosonic string theory, devised in the 1960s, suggests reality actually has 26 dimensions. It has a major problem, however. As its name suggests it only deals with particles called bosons – like the famous Higgs boson. It doesn't account for particles called fermions. It was largely superseded by superstring theory.

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The problem is we don't see evidence of any extra dimensions in our daily lives or in existing physics experiments like those conducted by Pardo. So if they're really there they must be curled up incredibly small so as to remain out of sight. Picture it this way. Look at a tree from a distance and it looks two dimensional - like it is painted onto a flat 2D canvas. But to an ant crawling on a branch, the tree would obviously be three-dimensional - it can crawl along, across and around the bark. It's all about scale. Could our universe appear painted on a three-dimensional canvas when actually there are more dimensions, hidden to all but those who live in the realm of the sub-atomic world?

The trouble with string theory is that it is famously hard to test. It says that particles such as electrons are made up of tiny vibrating strings. Just as you can play strings on a violin in different ways to produce different notes, so nature is creating a sub-atomic symphony of its own. But the number of different versions of string theory runs to 10^{500}. We don't yet know which configuration - if any - applies to our universe, and until we do we cannot perform an experiment to validate the idea. So what else can be done?

Enter the Large Hadron Collider (LHC) at CERN, near Geneva in Switzerland. The huge 27-kilometre (16.8 mile) particle race track was made world famous after its discovery of a particle called the Higgs boson in 2012. The Higgs was the last piece in a sub-atomic puzzle known as the Standard Model. This framework describes the particles that make up everything around us and their interactions with each other. Gravity, however, stubbornly refuses to be incorporated by it. That's just one of the many reasons why physicists

Gravitational lensing is one of the reasons astronomers think dark matter exists. Supersymmetry could provide the answer to what it's made of

> "Just as you can play strings on a violin in different ways, so nature is creating a sub-atomic symphony of its own"

Ask an astrophysicist: The multidimensional universe

Matt Kleban is an American theoretical physicist who works on string theory and theoretical cosmology. He is a professor of physics at New York University and director of the Center for Cosmology and Particle Physics

Why aren't we aware of other dimensions?

"In all the reasonable theories that require extra space dimensions, there's either a reason why we're stuck onto a three-dimensional subspace – in which case we simply don't notice the extra dimensions because we can't have move in those directions – or they're what we call compact. That means that if you go in that direction for a certain distance, you'll come back to where you started – a bit like if you go in a straight line on the surface of the Earth, and eventually circle the planet. Most people think that if there are extra dimensions, they must be compact on a very small scale so that we haven't noticed them."

How can we see these extra dimensions?

"The extra dimensions can play an important role in the early universe, and leave traces that we can detect. One example is a theory I've developed where inflation [the sudden burst of expansion that happened an instant after the Big Bang itself] relies on the extra dimensions. It's something moving around in an extra dimension that's causing inflation to happen, and that has implications for the structure of galaxies and galaxy clusters in the universe today. It wouldn't be a very direct detection, and there would be a lot of argument as to whether it really showed that there were extra dimensions, but in principle, with enough data and some luck, you could discover them that way."

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Bluffer's guide to string theory

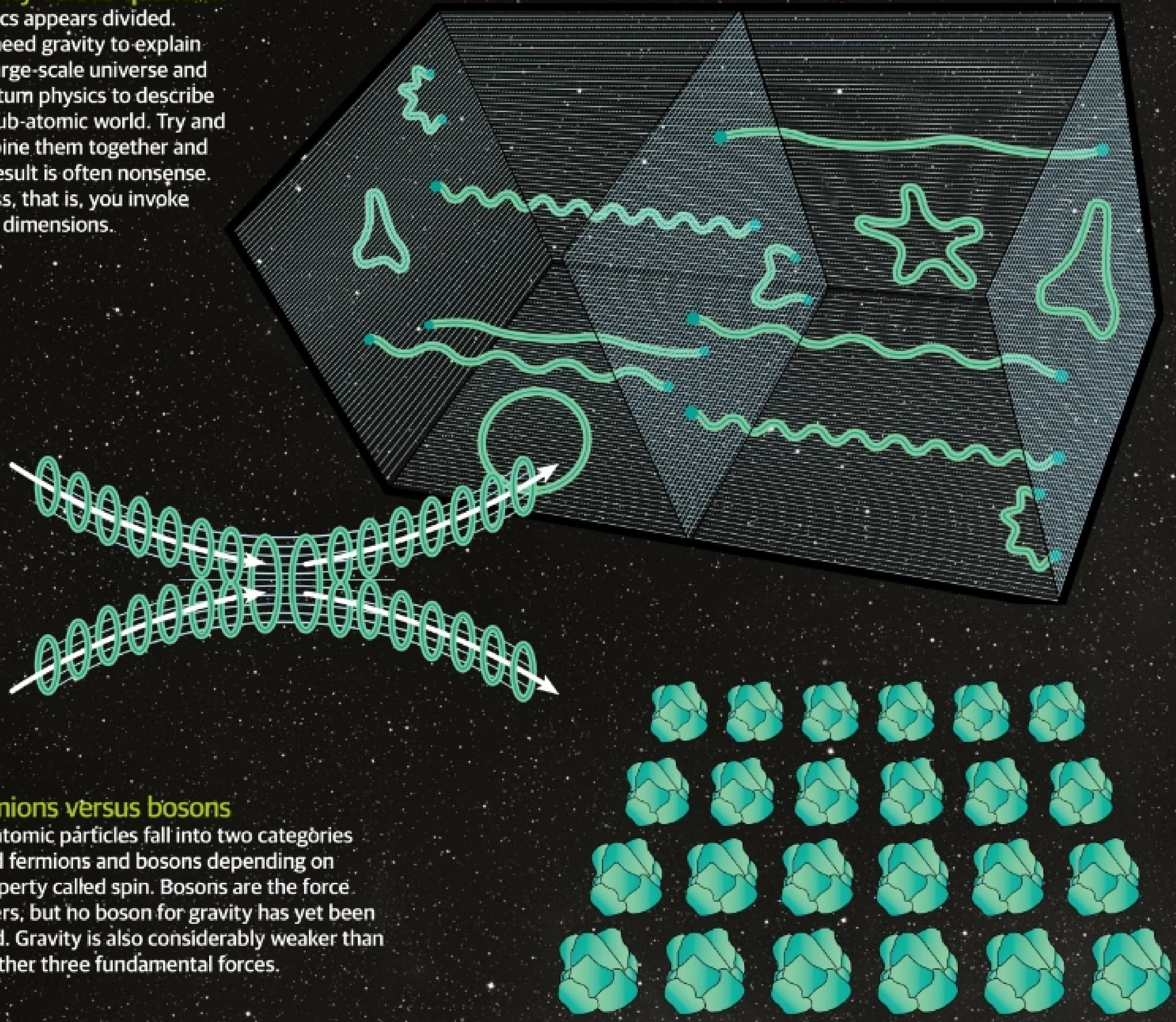
Your quick and easy guide to the ins and outs of superstring theory

Gravity versus quantum

Physics appears divided. You need gravity to explain the large-scale universe and quantum physics to describe the sub-atomic world. Try and combine them together and the result is often nonsense. Unless, that is, you invoke extra dimensions.

How does string theory help?

By replacing particles with tiny strings that vibrate across multiple dimensions you can, at least on paper, solve many of these otherwise intractable problems. If ultimately successful it could shed light on the bottom of black holes and the beginning of the universe.



What do you mean by extra dimensions?

Our lives play out across four dimensions. To tell someone else where an object is you can give three co-ordinates to locate it in space and one to anchor it in time. Superstring theory says there are six additional dimensions that we don't experience or have access to.

Fermions versus bosons

Sub-atomic particles fall into two categories called fermions and bosons depending on a property called spin. Bosons are the force carriers, but no boson for gravity has yet been found. Gravity is also considerably weaker than the other three fundamental forces.

Is it testable?

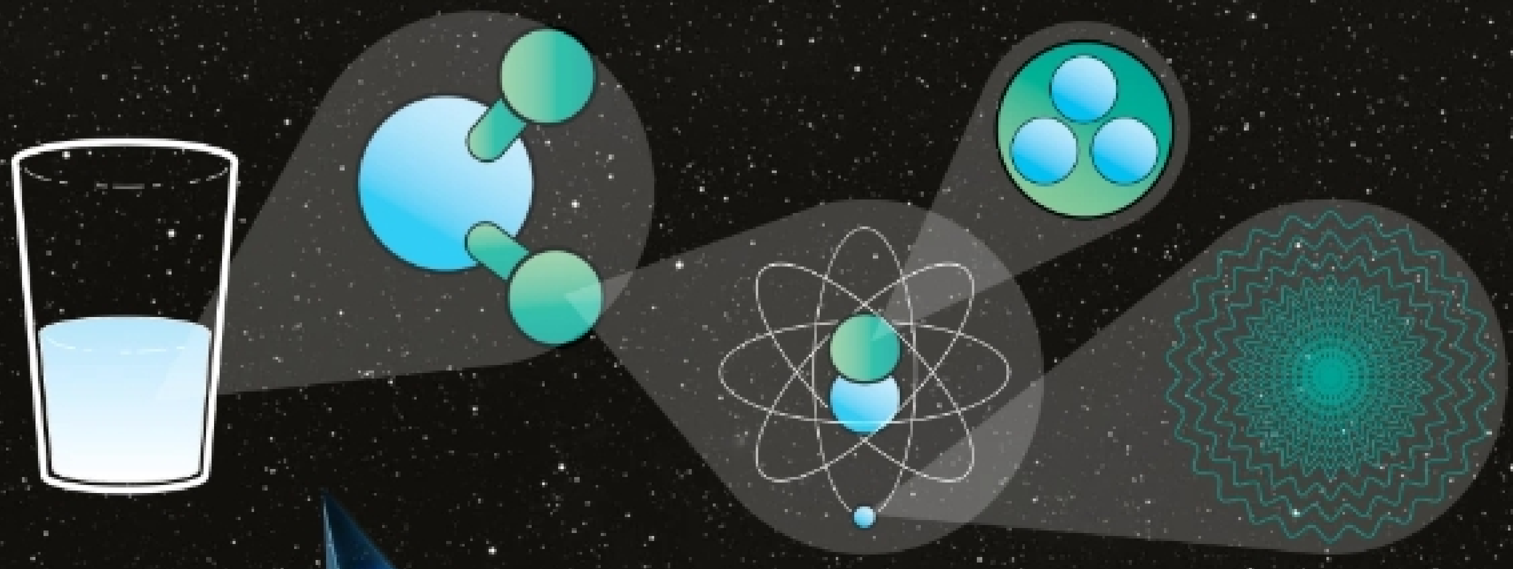
This is the major accusation levied at string theorists. At the moment it isn't falsifiable through experiment, leading some to question whether it's even science. Even finding evidence of supersymmetry wouldn't prove superstring theory correct.

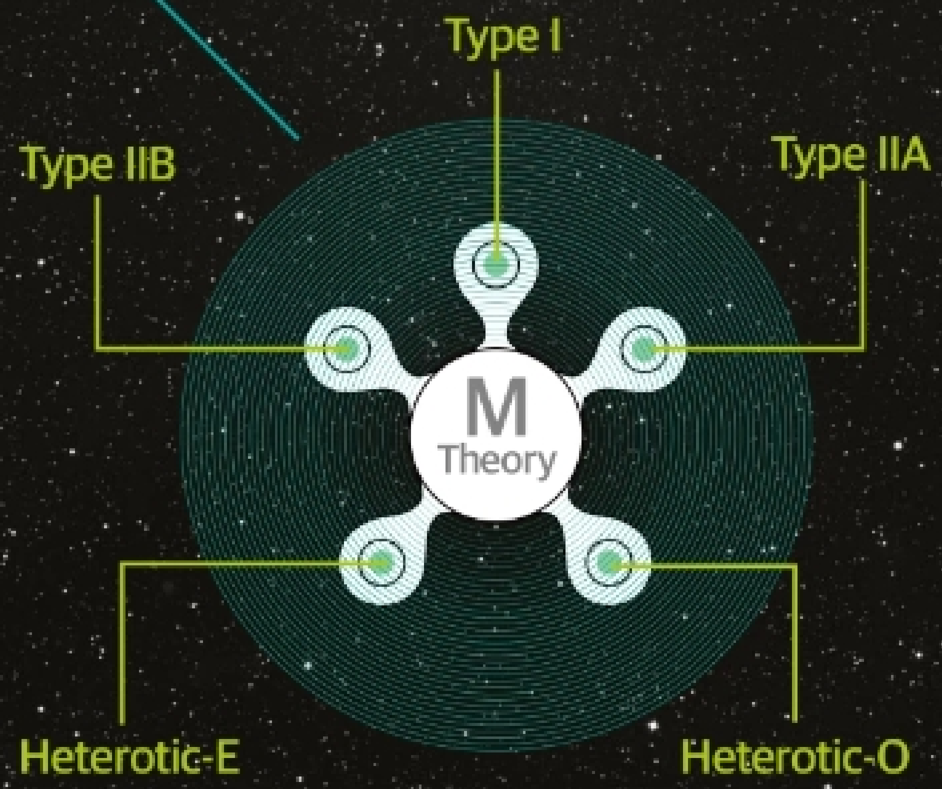
What about M-theory?

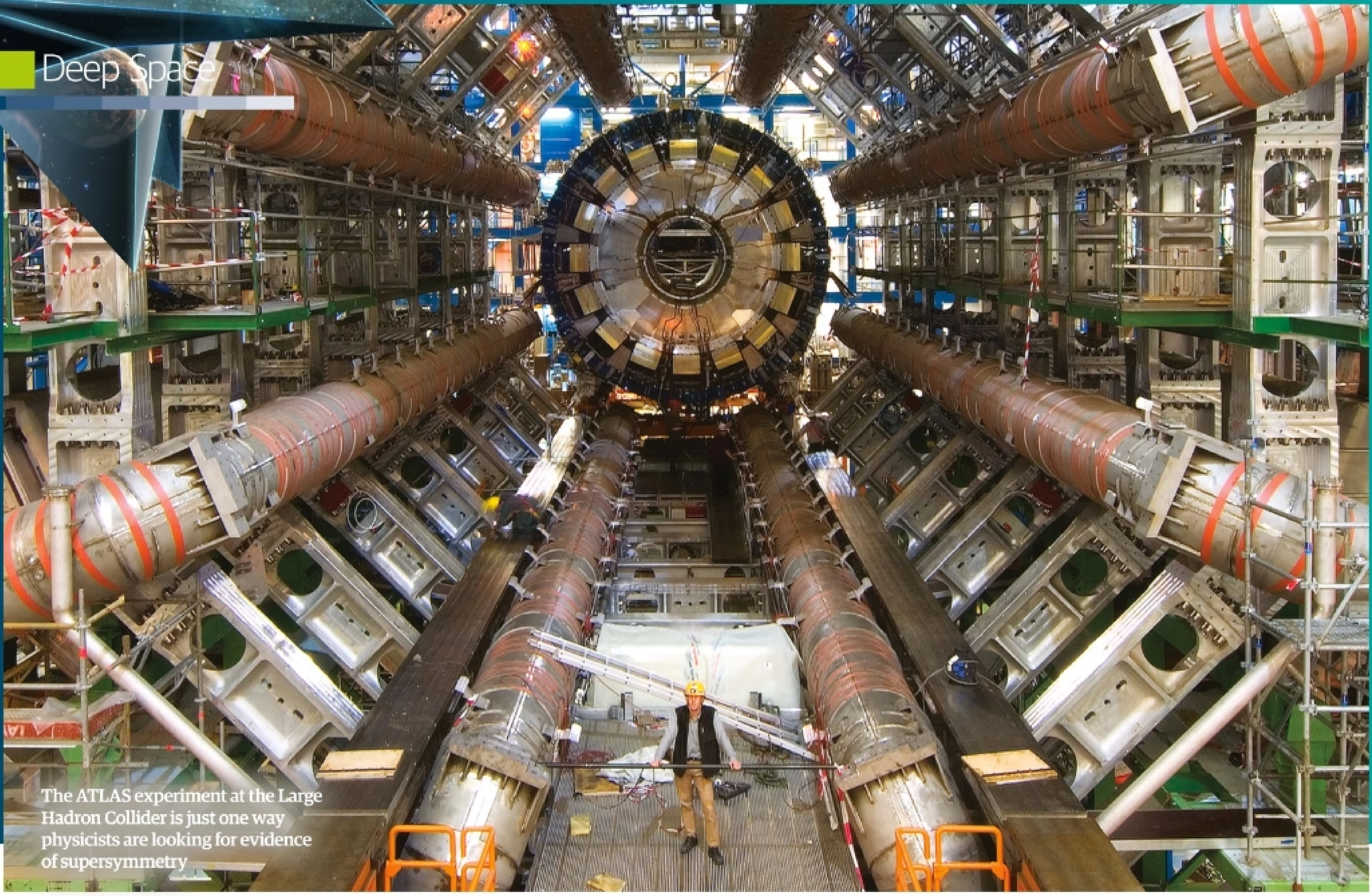
There are five different versions of superstring theory, but they might all be manifestations of the same thing: M-theory. It introduces an additional dimension, taking the total to 11.

What's the super about?

It comes from a theory called supersymmetry, which aims to find physics beyond the Standard Model. Superstring theory is an improvement on plain old string theory because it accounts for both bosons and fermions.







The ATLAS experiment at the Large Hadron Collider is just one way physicists are looking for evidence of supersymmetry

"There are some theories of extra dimensions that you can't probe with the large scales that we worked with" **Kris Pardo**

around the world are looking for physics beyond the Standard Model. Another is the search for dark matter, the mysterious shadowy entity that acts like a glue holding large structures in the universe together. "There's nothing in the Standard Model to explain that," says Tina Potter from the University of Cambridge, UK.

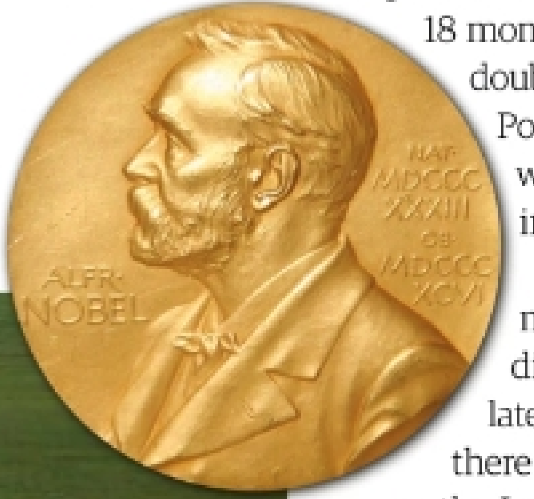
She is working on the ATLAS experiment at the LHC in the hope of finding evidence of a theory called supersymmetry – the most popular theory of physics beyond the Standard Model. It says that every particle in the Standard Model has an as-yet-undiscovered partner. That instantly doubles the number of particles physicists are searching for. "Some of these particles are fantastic candidates for dark matter – so if we find them it would plug one of the big holes in our knowledge about the universe," Potter says.

It isn't the theory's only appeal – some versions of string theory also rely on supersymmetry being true. Those that do are called supersymmetrical string theories – or superstring theories. There are five versions in total. However, in order to get the maths to work, all five superstring theories require there to be ten dimensions. That's the three of space and one of time we experience, plus six so-called 'hyperspace' dimensions that we don't. Those hyperspace dimensions would be small enough to remain out of sight. An alternative theory known as M-theory suggests that all five superstring theories are variants of an 11-dimensional reality. These superstring theories became fashionable in the 1980s and overtook the original version of string theory in popularity. That's called bosonic string theory, and it suggests the strings vibrate across a staggering 26 dimensions!

Finding evidence of supersymmetry won't in itself confirm superstring theory, but a failure to do so would make the whole idea even harder to stomach. In that regard the LHC may be able to help. It has just reached the end of its latest run of particle-smashing experiments, producing a swarm of important data for physicists to pick over.

"We are hoping to find something there," says Potter. "It's all hands on deck to analyse it as quickly as possible." Meanwhile, the LHC will be shut down in December 2018 and upgraded ready to produce even more energetic collisions in around 18 months' time. "Next time we turn on we'll double the amount of data we have now," Potter says. "Any hints of supersymmetry we see in this dataset will be confirmed in the next one."

So slowly but surely physicists are making headway. Larger additional dimensions appear ruled out by the latest gravitational wave discoveries, but there remains hope that experiments such as the Large Hadron Collider could confirm supersymmetry and bolster the somewhat flimsy circumstantial case for string theory with its smaller hyperspaces. As always in physics, more experiments and better data bring sharper insights. They could one day prove that Nature paints on a canvas of many more dimensions than meet the eye. Curiouser and curiouser indeed.



A neutron star merger known as GW170817 was picked up by the LIGO detector in 2017

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BEYOND DEEP SPACE

How technology is helping us peer to the edges of the observable universe

Reported by Abigail Beall

© NASA, ESA

From neutrinos produced just seconds after the Big Bang to the most distant superclusters of galaxies we know of, studying the edge of our universe is an exciting task for astronomers around the world. And thanks to advancements in technology, we know more than ever about what lies at the boundaries of our cosmos.

When you look at something, you are looking back in time. This holds true for anything you see, it's just the distances involved are mostly so small and light moves so quickly, you will never notice the time it takes to reach you. When you begin to look into space, the time difference starts to matter. Looking at the Moon, you are seeing it about 1.3 seconds back in time. Light takes just over eight minutes to reach us from the Sun, and to Jupiter it's about 43 minutes.

However, these kinds of time scales are nothing compared to the amount of time it's taken light to reach Earth from the most distant stars and galaxies we can see.

Based on calculations, astronomers believe the universe is 13.8 billion years old. Light moves at the speed of light, travelling 299,792 kilometres (186,282 miles) every second. In one year light travels the distance of one light year, or 9.46 trillion kilometres (5.88 trillion miles). It sounds like a huge number, but in the scale of the universe one light year is nothing. This means even with the most powerful telescopes, there is a limit to how far away we can see based on the time it takes light to reach us. This means there's a sphere around Earth, beyond which we simply cannot see. This is called the observable universe.

To complicate matters, the universe is also expanding, and accelerating in its rate of expansion too. This means since light was released 13.8 billion years ago, the position from which that light came has now moved further away. In astronomy, this is known as the comoving distance. Astronomers estimate the distance to the edge of the observable universe is 45.7 billion light years.

The most distant confirmed galaxy we know of is called GN-z11, and it is an estimated 32 billion light years from Earth. It was first imaged by the Hubble Space Telescope. After that there is MACS1149-JD1, at 30 billion light years. The most distant object that is not a galaxy is a gamma-ray burst, seen at 13.18 billion light years away, detected in April 2009.

But peering to the galaxies and gamma-ray bursts at the edge of the universe is by no means the only way to find out more about the early stages of the universe.

One method used by astronomers to peer to the edge of the universe is by studying the Cosmic

Microwave Background (CMB). The CMB is electromagnetic radiation that has been left over from an early stage in the universe's lifetime, about 380,000 years after the Big Bang, and for that reason it's also referred to as an echo of the Big Bang. It was first discovered in 1964, by accident, when Arno Penzias and Robert Wilson were using a telescope in the microwave range and noticed interference coming from every part of the sky.

"When we first heard that inexplicable 'hum,' we didn't understand its significance, and we never dreamed it would be connected to the origins of the universe," Penzias said in a statement. "It wasn't until we exhausted every possible explanation for the sound's origin that we realised we had stumbled upon something big." It was big indeed, and in 1978 the pair won the Nobel Prize for their discovery.

Looking at the CMB, astronomers can learn about a time just after the Big Bang, when photons were first able to move around freely. It looks roughly the same in any direction you look. Then, between 2009 and 2013 the European Space Agency's Planck observatory undertook the most detailed study of the CMB to date. In a paper published in June this year, a new analysis of this data shows anomalies, like a cold spot, which astronomers are still struggling to explain.

Although the CMB gives us unique insight into the early stages of the universe, there are other ways to find out about what lies at the edges of our observable universe.

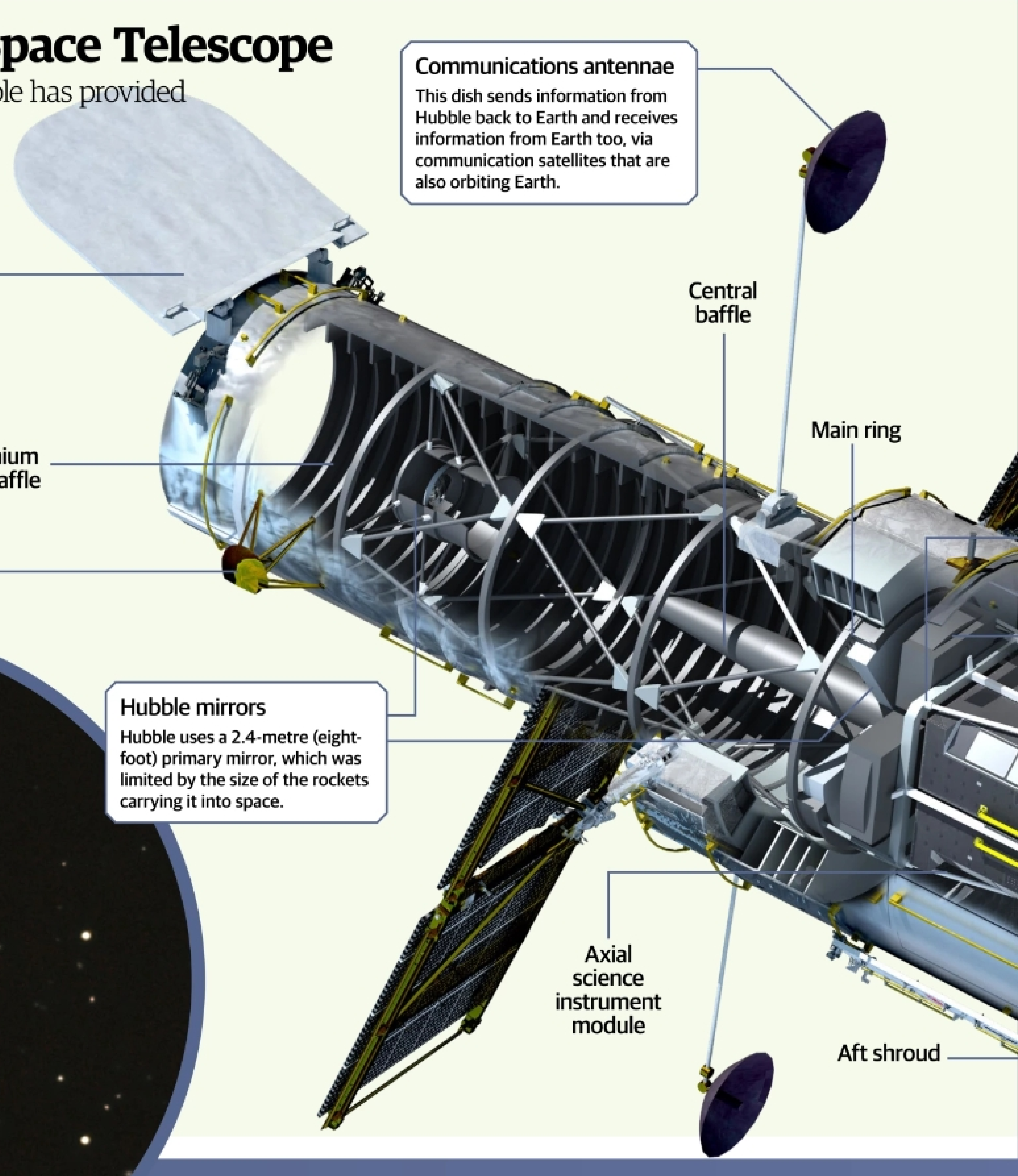
In June 2018, a group of astronomers announced a discovery that challenges assumptions researchers had made about the early history of the universe. The team, led by Scott Chapman at Dalhousie University in Canada, were able to find a supercluster of 14 galaxies 90 per cent of the way to the edge of the observable universe. Called a galactic protocluster, the 14 galaxies are a precursor to galaxy clusters, the largest known objects in the universe. These galaxies were seen 12.4 billion light years away, only 1.4 billion years after the start of the universe.

According to previous models of how the universe evolved, protoclusters like this were not expected to have existed as early as then. The discovery of the cluster, called SPT2349-56, proved the evolution of galaxy clusters happens

> "We didn't understand its significance, and we never dreamed it would be connected to the origins of the universe" **Arno Penzias**

The Hubble Space Telescope

Launched in 1990, Hubble has provided us with years of science



Communications antennae
This dish sends information from Hubble back to Earth and receives information from Earth too, via communication satellites that are also orbiting Earth.

Light shield
This prevents unwanted light from entering the telescope and messing with the images taken by the extremely sensitive instruments.

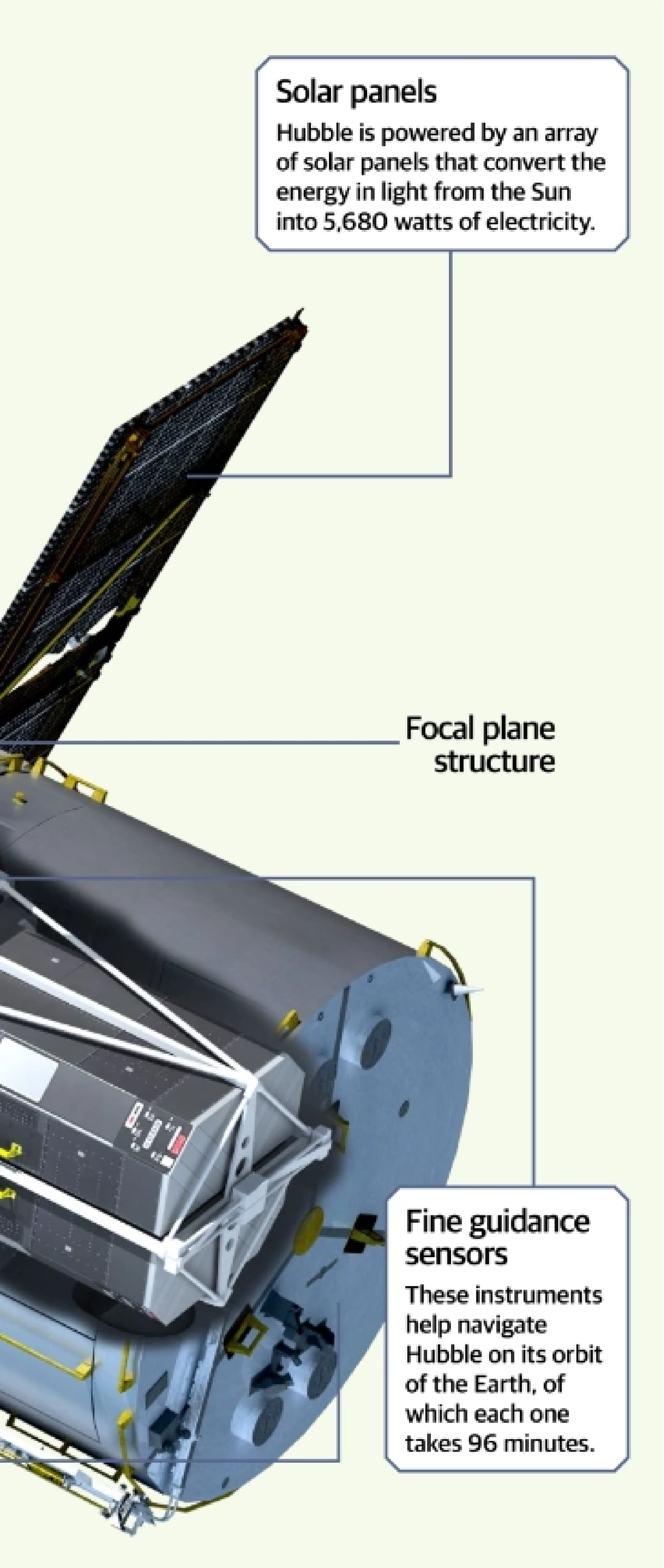
Hubble mirrors
Hubble uses a 2.4-metre (eight-foot) primary mirror, which was limited by the size of the rockets carrying it into space.

© ESO, Illustration by Adrian Mann

Right: Composite image of ULAS J1120+0641, which has a black hole at its centre with a mass of 2 billion times that of the Sun much more quickly than astronomers had previously believed.

Chapman says the only way he and his team were able to make this discovery was because of technology. "The South Pole Telescope is how we discovered it, and the upgrades going on, called SPT-3G, will enable more of these types of discoveries," he says. The South Pole Telescope is a ten-metre (33-foot) diameter telescope at the Amundsen-Scott South Pole Station in Antarctica. It looks in the microwave, millimetre, and sub-millimetre ranges of electromagnetic radiation, and was originally designed for observing the CMB. The third generation of the telescope was installed in 2017, including ten-times the number of sensors, which means it can map a section of the sky ten-times faster than before. In 2018, a new survey began using this new camera.

"But SPT couldn't do it on its own," says Chapman. "Other ESO [European Southern



Solar panels
Hubble is powered by an array of solar panels that convert the energy in light from the Sun into 5,680 watts of electricity.

Fine guidance sensors
These instruments help navigate Hubble on its orbit of the Earth, of which each one takes 96 minutes.

Picture gallery: beyond deep space

Looking out as far as we can, astronomers have found galaxies almost as old as the universe itself

GN-z11 is a high-redshift galaxy found in the constellation Ursa Major. GN-z11 is currently the oldest and most distant known galaxy in the observable universe.

© NASA/ESA

When GRB 090423, seen here as an artist's impression, was detected it was a signature of the explosion of the earliest, most distant known object in the universe.

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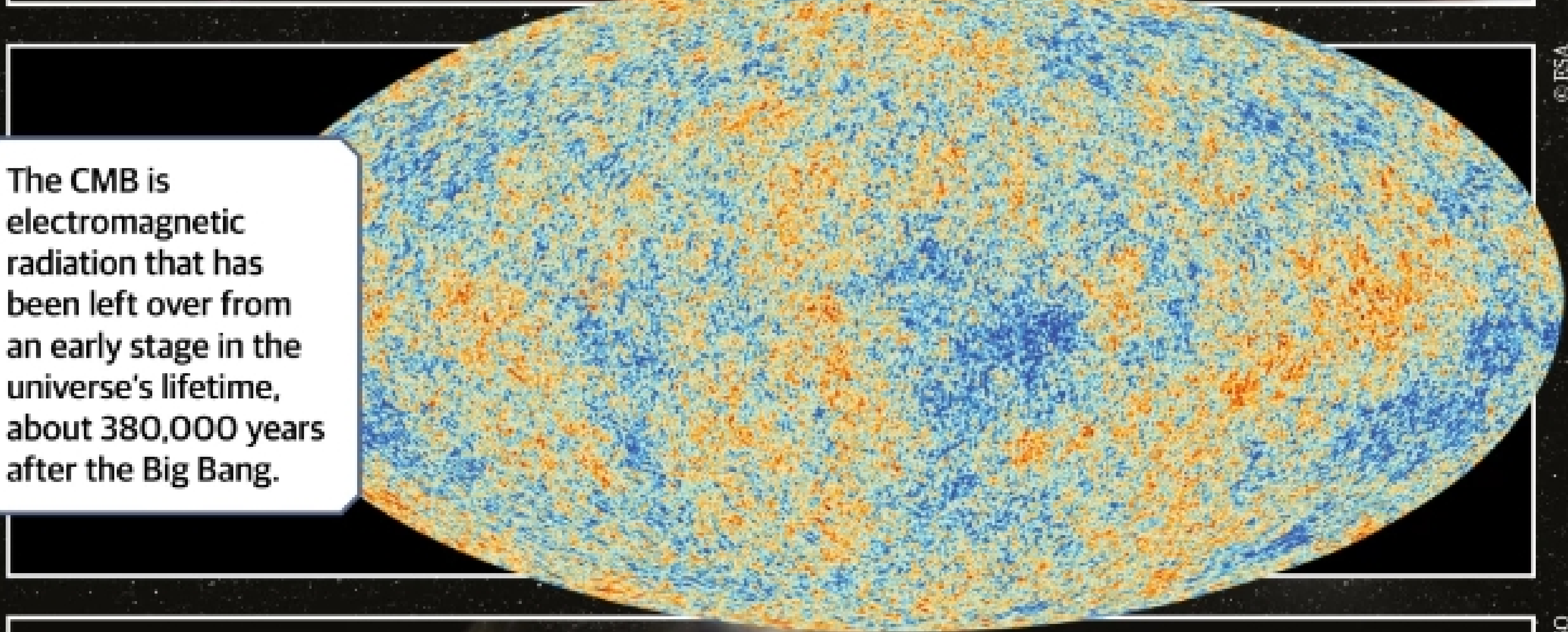

The CMB is electromagnetic radiation that has been left over from an early stage in the universe's lifetime, about 380,000 years after the Big Bang.

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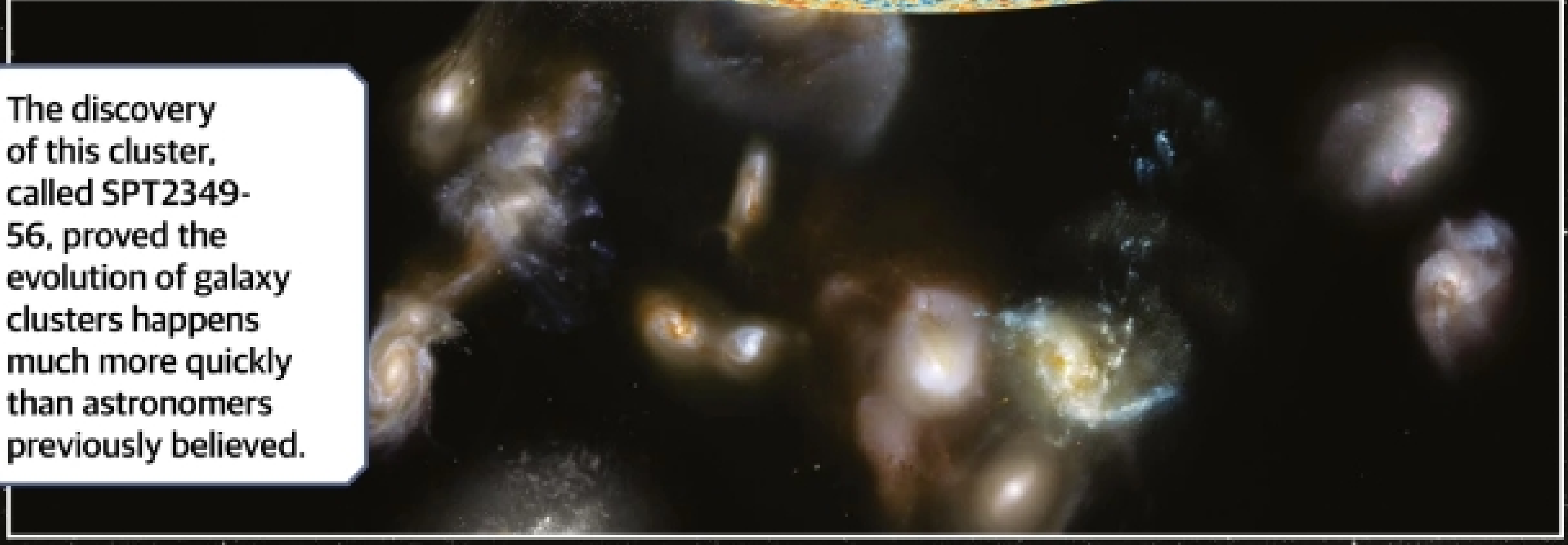

The discovery of this cluster, called SPT2349-56, proved the evolution of galaxy clusters happens much more quickly than astronomers previously believed.

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MACS1149 is one of the farthest known galaxies from Earth, about 30 billion light years away.

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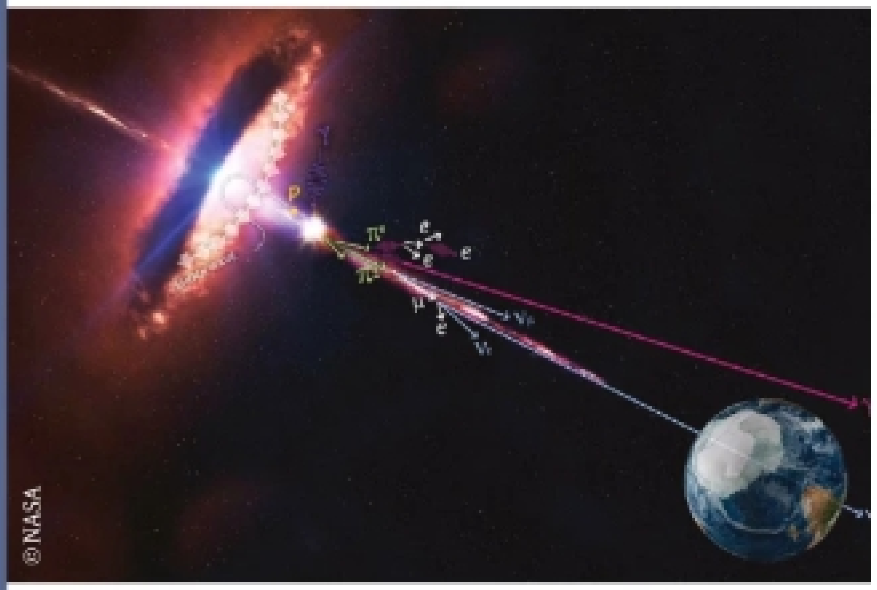
Observatory] and international facilities were the keys to unlocking the details of this and other superclusters near the edge of the observable universe." These include the Atacama Pathfinder Experiment (APEX) and the Atacama Large Millimeter/submillimeter Array (ALMA), both based in the Atacama desert of northern Chile. ALMA is an interferometer made up of 66 radio telescopes working together, sitting at 5,058 metres (16,600 feet) above sea level, while APEX is a radio telescope at an elevation of 5,100 metres (16,730 feet). Chapman is excited about technological developments in this region, too.

"A new telescope going high above ALMA in Chile, CCAT [Cerro Chajnantor Atacama Telescope], will also permit new ambitious surveys that will open up the discovery of space even more," he says. The six-metre (19.7-foot) telescope is designed to observe at submillimetre to millimetre wavelengths and will be built in the Atacama desert at an elevation of 5,600 metres (18,400 feet). The telescope, which will be roughly 12-metres (39.4-feet) tall, is expected to gather its first light in 2021.



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Chapman is expecting to publish an update to his study soon, a detailed follow-up of the previous study. While it's not yet published, we can be sure it's going to be an exciting announcement.

Due to be completed in 2021, NASA's James Webb Space Telescope is also hoping to study the galaxies that formed in the earliest universe. It is extending the work done by the Hubble Space Telescope and will be looking at longer wavelengths of light than its predecessor. The telescope's main focus will be the time during which most galaxies began to form, which will hopefully help answer the questions brought about by studies like Chapman's and shine light on how galaxy formation happens.

But it's not all about light. Studying neutrinos, fundamental particles that barely interact with anything, only through the weak force and gravity, can teach us about the edge of the universe too.

In March this year, Daniel Green from the University of California San Diego led a study using neutrinos as 'messengers from the early universe'. In the hot gas that filled the early universe, neutrinos travelled near the speed of light while everything else moved more slowly. They are uniquely placed to teach us about that stage of the universe.

"We looked for the signal of cosmic neutrinos in distribution of galaxies in the universe" says Green. "We used data from one particular survey, BOSS, which measured the locations of approximately 1 million galaxies very precisely." The Baryon Oscillation Spectroscopic Survey (BOSS) was part of the third Sloan Digital Sky Survey and gathered data from 2009 to 2014 at the Apache Point Observatory in New Mexico, United States.

Because of the high speeds they moved at, the neutrinos affected how matter moved on very large distances. Green and his colleagues isolated a signal in the galaxies that could only have been caused by a particle moving at the speed of light in the early universe. This means the neutrino was the only option for the cause of these signals.

The cosmic neutrinos are imprinted in the locations of the galaxies found during the observations. From studying the neutrinos the astronomers can tell where they came from. "We used a new type of data analysis technique, built on earlier work, to extract the signal of the neutrinos from these maps of the universe" Green says.

There are many approaches to making maps of the universe and different technologies that make them possible. "The most important thing with this particular survey is that it can measure the spectrum of a large number of galaxies, which gives very accurate measurements of the distances," says Green.

The results from this study confirm the idea that the universe was heated to a very high temperature and then cooled through expansion. "In particular,

> "A new telescope in Chile will permit new ambitious surveys that will open up the discovery of space even more" **Scott Chapman**

Above: Artist's impression of a blazar shooting a beam of cosmic rays at the Earth, an example of multi-messenger astronomy using neutrinos and electromagnetic raditaion

Right: Various long-exposure campaigns, like the Hubble eXtreme Deep Field (XDF) shown here, have revealed thousands of galaxies in a fraction of a millionth of the sky

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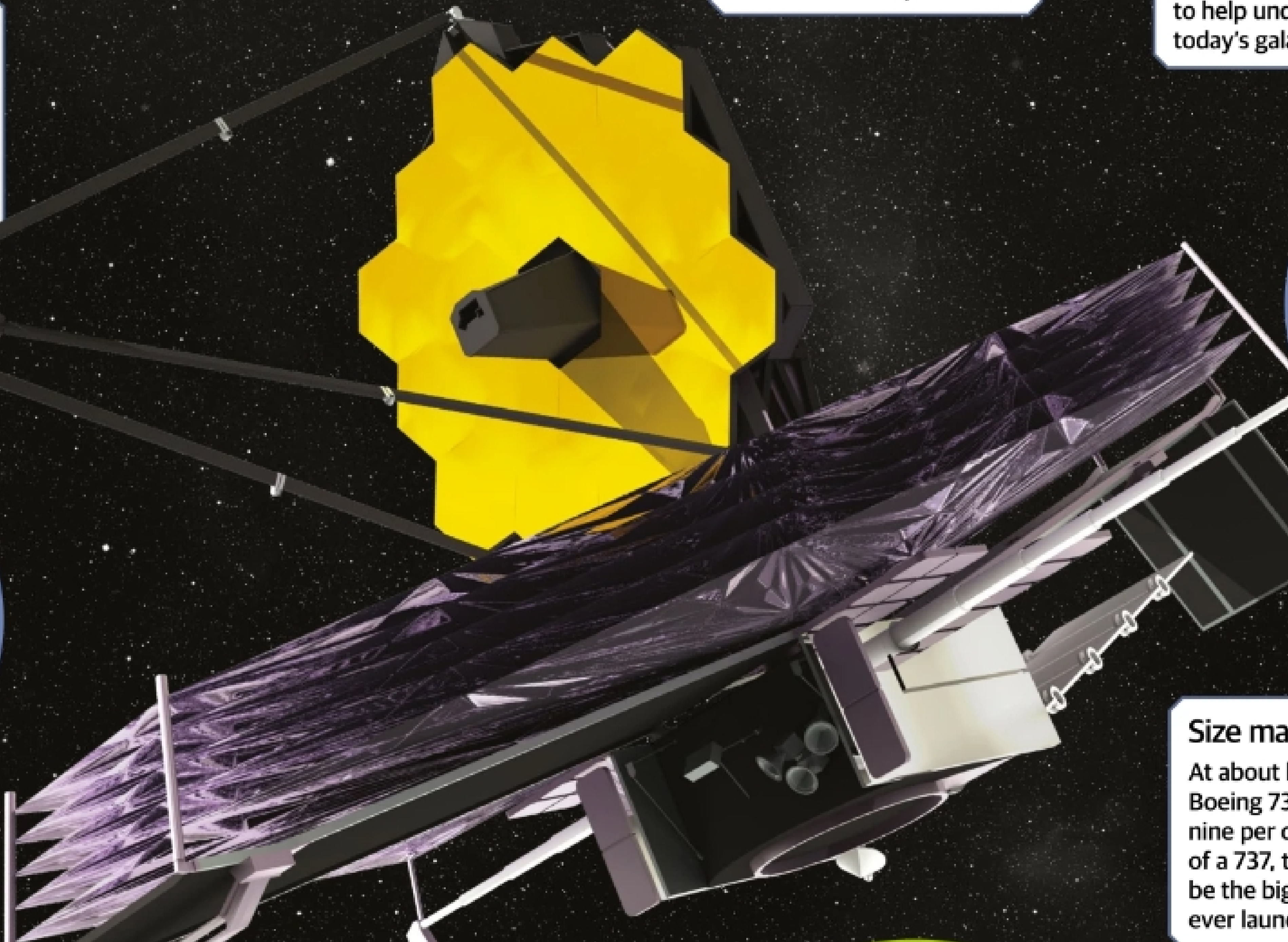
How the James Webb can help

Expected to launch in 2021, the next-generation telescope will look at galaxies as they first formed



A better mirror

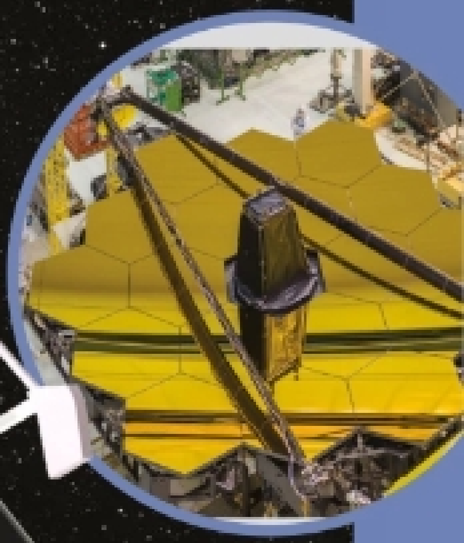
The JWST's 18-segment primary mirror will be over six-times bigger in area than Hubble's and around 100-times more powerful.

Unprecedented sensitivity

The sensitivity of the instruments will allow astronomers to see the faintest, earliest galaxies to help understand how today's galaxies formed.

Infrared vision

The JWST will study the infrared part of the electromagnetic spectrum to peer back at galaxies over 13.5 billion years old.



Size matters

At about half the size of a Boeing 737, yet less than nine per cent of the mass of a 737, the JWST will be the biggest telescope ever launched into space.

A million miles away

The JWST will orbit the Sun, 1.5 million kilometres (1 million miles) from Earth, meaning its vantage point will be completely different to any before.

A collaboration

Over 1,200 skilled scientists, engineers and technicians from 14 countries have been involved with building the telescope.

© NASA; Illustration by Adrian Mann

this batch of neutrinos was released about a second after the Big Bang and is the earliest moment in the history of the universe, to date, where we have confirmed this story," says Green.

Data analysis is crucial in allowing advancements in astronomy, as the more information researchers gather, the more difficult it becomes to analyse that data. Increasingly, astronomers are relying on technology like artificial intelligence to help interpret and analyse data that would otherwise have taken researchers years to work through. Aside from improvements in the technologies used in the telescopes, this kind of technology is one of the most important areas in which astronomy research is developing.

There is a lot of hype about artificial intelligence. Whether it could bring us self-driving cars or be used to replace human jobs or to spy on members of the public, the possibilities of a future with AI are difficult to guess, and are often quite daunting. However, at least within astronomy, the technology is being used for good.

For example, a study in 2017 showed AI could be used to sift through data collected by gravitational wave detectors like the Laser Interferometer Gravitational-Wave Observatory (LIGO). These waves are ripples in space-time caused by large-scale events like the collision of two black holes. Using AI to help comb through data will enable more detections using multi-messenger astronomy - looking at the same event through multiple different signals including gravitational waves, electromagnetic radiation and neutrinos.

Together with improvements in technology regarding telescopes, like the upgrades to the South Pole Telescope and the new telescope in Chile, better data analysis techniques will enable astronomers to continue to peer as far back as possible and learn more about the distant universe in the next few years.

What could be at the edge of the universe?

Young galaxies

Peering to the edge of the observable universe gives us a unique insight into the very earliest days of the cosmos, a time when galaxies were just starting to form.

Superclusters

A study last year found a supercluster of 14 galaxies beginning to form together, making it the most distant supercluster ever discovered.

Neutrinos

Just seconds after the Big Bang, neutrinos were released, and now we can see them coming from distant galaxies to learn more about the early universe.

FutureTech

The technology that will revolutionise space travel and exploration

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A new initiative has been launched to develop real-life robots that allow humans to venture into space… without actually leaving Earth

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Elon Musk has teased the world with sneak peeks of what the spaceship to take humans to Mars could look like

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Take a look at NASA's great observatories of the future

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Low-Earth orbit construction will hopefully begin in 2020, where it will eventually accommodate three astronauts

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A joint ESA and UKSA engine that's able to breathe air is set to revolutionise spaceflight as we know it

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A swarm of telescopes placed billions of kilometres away will be able to reveal a universe full of exoplanets

"With 2020 not far off, China is preparing for its next space outpost"

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> “It will unite robotic space survivability with human ingenuity to create a whole new age of space exploration”

© JAXA; Clouds Architecture Office; Adrian Mann; Hluboki / Getty

AVATARS IN SPACE

A new initiative has been launched to develop real-life robots that allow humans to venture into space… without actually leaving Earth

Written by Lee Cavendish

Space can be a dangerous place for a human. There are a number of factors in the way of human exploration of space. Even before you leave Earth's gravity the initial ascent on a tin rocket packed with flammable fuel could end badly. Once in space the protective layer of the atmosphere is gone and you are subject to harsh radiation. With further advances in technology year after year there is a strong argument for the development of an intelligent robotic presence in space. Not artificial intelligence, but humans controlling a robotic body. This is why the Japan Aerospace Exploration Agency (JAXA) and All Nippon Airways (ANA) have launched the AVATAR X program. This initiative to create ground-controlled robots in space will revolutionise space exploration and discovery.

Space probes have been scientists' main source of exploration for decades now; with the rapid improvement of technologies there is a swarm of orbiters, landers and rovers scattered throughout the Solar System. Just above Earth, gliding through low-Earth orbit, is the International Space Station (ISS), capable of accommodating six astronauts at a time. In the outer Solar System NASA's Juno spacecraft is gathering valuable data about the gas giant Jupiter, and even farther beyond that the New Horizons spacecraft is making the first approach to a Kuiper Belt object nicknamed Ultima Thule. By looking at these examples, it is safe to say that man-made spacecraft are better suited to exploring the cosmos than humans are.

But how does it get better? With evolving technologies comes the evolution of human innovation and creative thinking, and this is exactly what the ANA-JAXA AVATAR X program will bring to the table. Although the programme is in its early stages of development its ambitions are clear – to put a real-life, robotic avatar into space for humans to control back on Earth. It will unite robotic space survivability with human ingenuity to create a whole new age of space exploration.

This idea came about as a result of ANA's AVATAR Vision and JAXA's new research and development programme, JAXA Space Innovation through Partnership and Co-creation, or J-SPARC. It is not just these two organisations that are involved; there are a whole host of names that include Meltin, a company specialising in developing cyborg technology, and XPRIZE, the same company that cofounded the Google Lunar XPRIZE. The ANA Avatar XPRIZE is a $10 million (£7.9 million) prize for the clever mind, or minds, that can develop real-life avatars over a four-year global competition.

"Our ability to physically experience another geographic location, or to provide on-the-ground assistance where needed is limited by cost and the simple availability of time," says XPRIZE founder and executive chairman Dr Peter H. Diamandis. "The ANA Avatar XPRIZE can enable creation of an audacious alternative that could bypass these limitations, allowing us to more rapidly and efficiently distribute skill and hands-on expertise to distant geographic locations where they are needed, bridging the gap between distance, time and cultures."

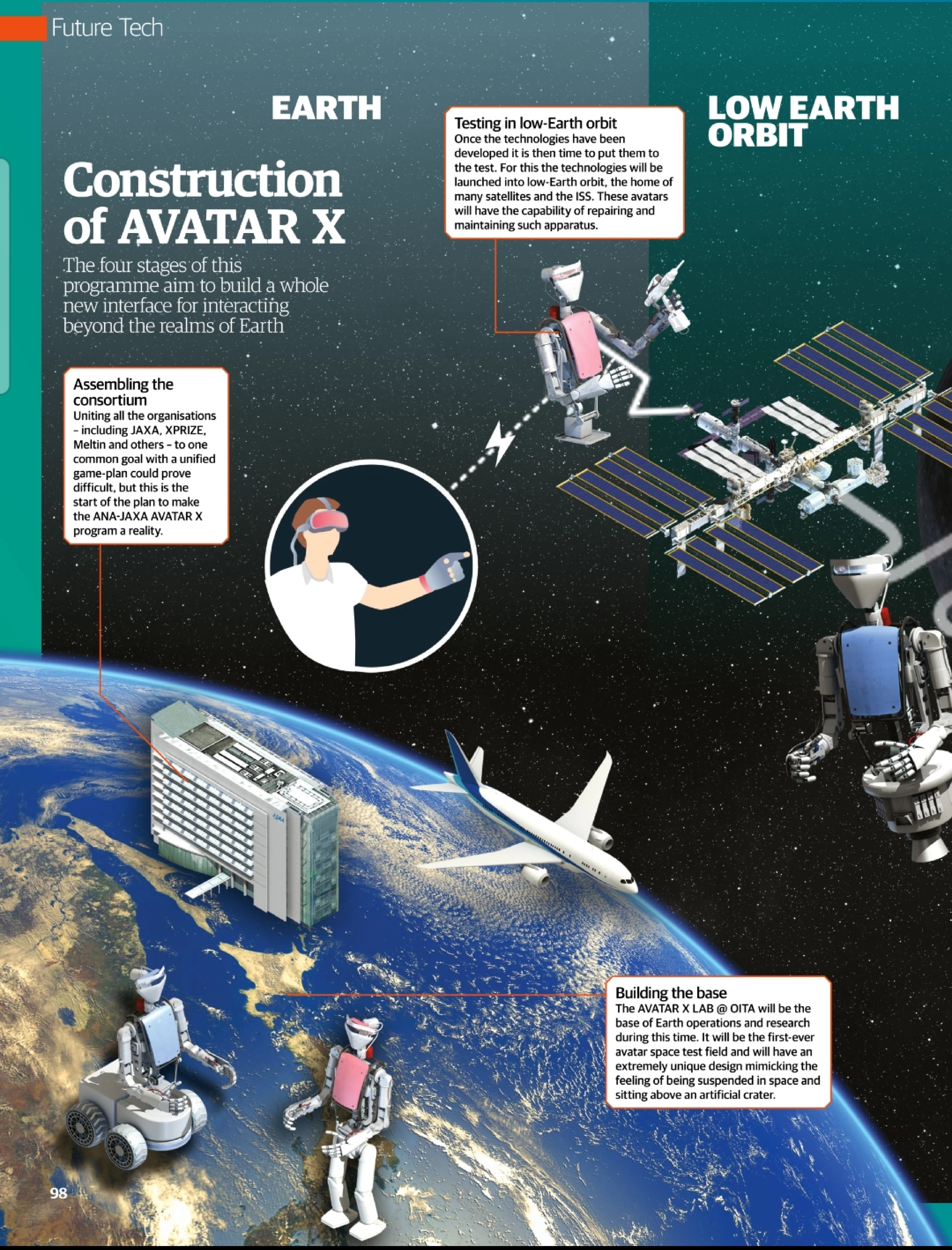
To make this science-fiction idea a reality there are many phases to the plan, which begins with developing a base on Earth, as well as the actual avatars. Then comes the testing beyond the confines of Earth. When up and running the AVATAR X team hope that the avatars will aid construction in space, including on the lunar surface and beyond; the operation and maintenance of space stations from Earth, such as the ISS and the future Deep Space Gateway and even space-based entertainment and travel for the public, benefiting from the commercialisation of space.

The first phase in this plan is assembling the AVATAR X consortium, which has already started

The research and development site will develop the ideas outlined by the AVATAR X consortium

Construction of AVATAR X

The four stages of this programme aim to build a whole new interface for interacting beyond the realms of Earth



EARTH

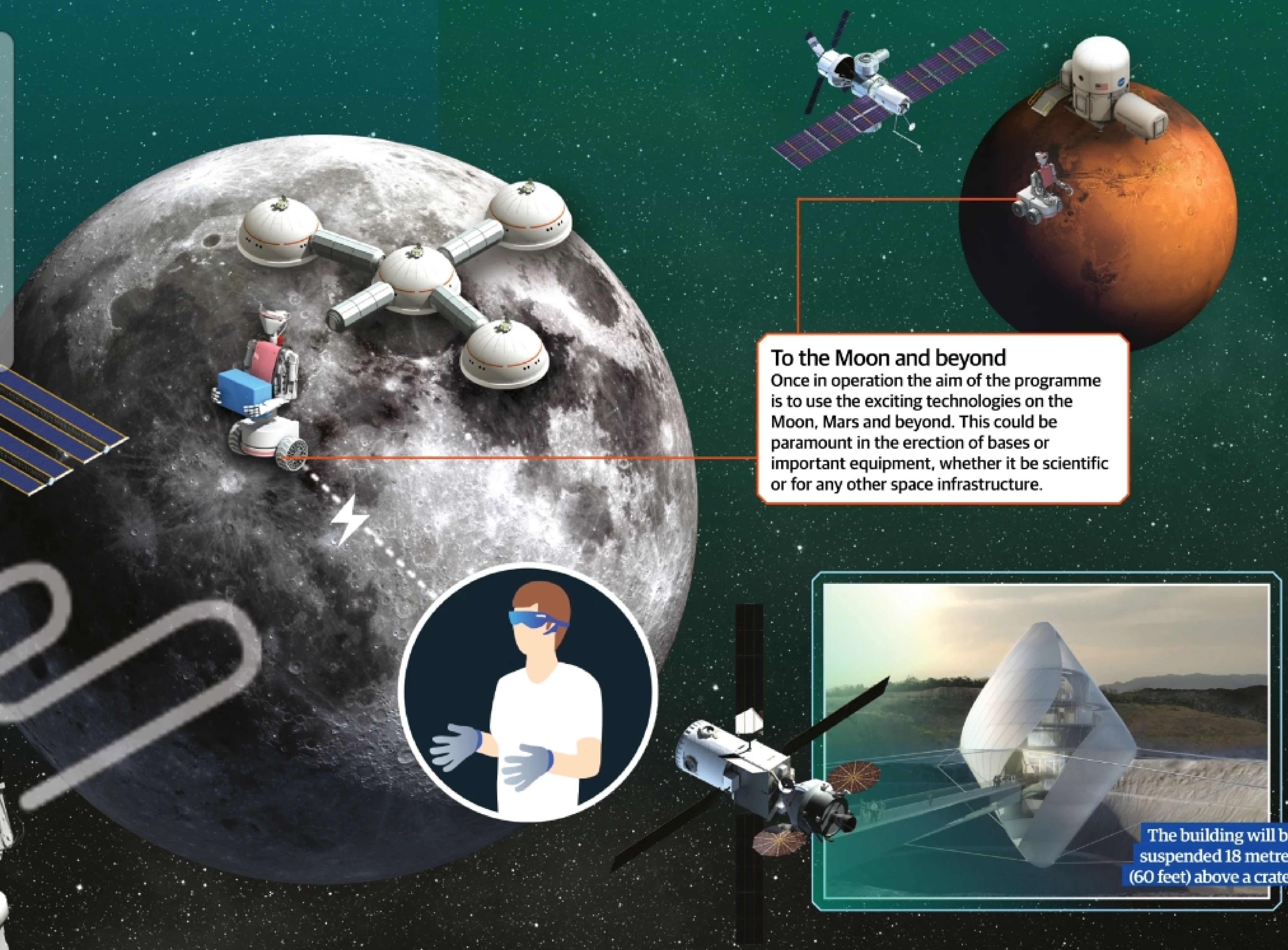
LOW EARTH ORBIT

Assembling the consortium
Uniting all the organisations – including JAXA, XPRIZE, Meltin and others – to one common goal with a unified game-plan could prove difficult, but this is the start of the plan to make the ANA-JAXA AVATAR X program a reality.

Testing in low-Earth orbit
Once the technologies have been developed it is then time to put them to the test. For this the technologies will be launched into low-Earth orbit, the home of many satellites and the ISS. These avatars will have the capability of repairing and maintaining such apparatus.

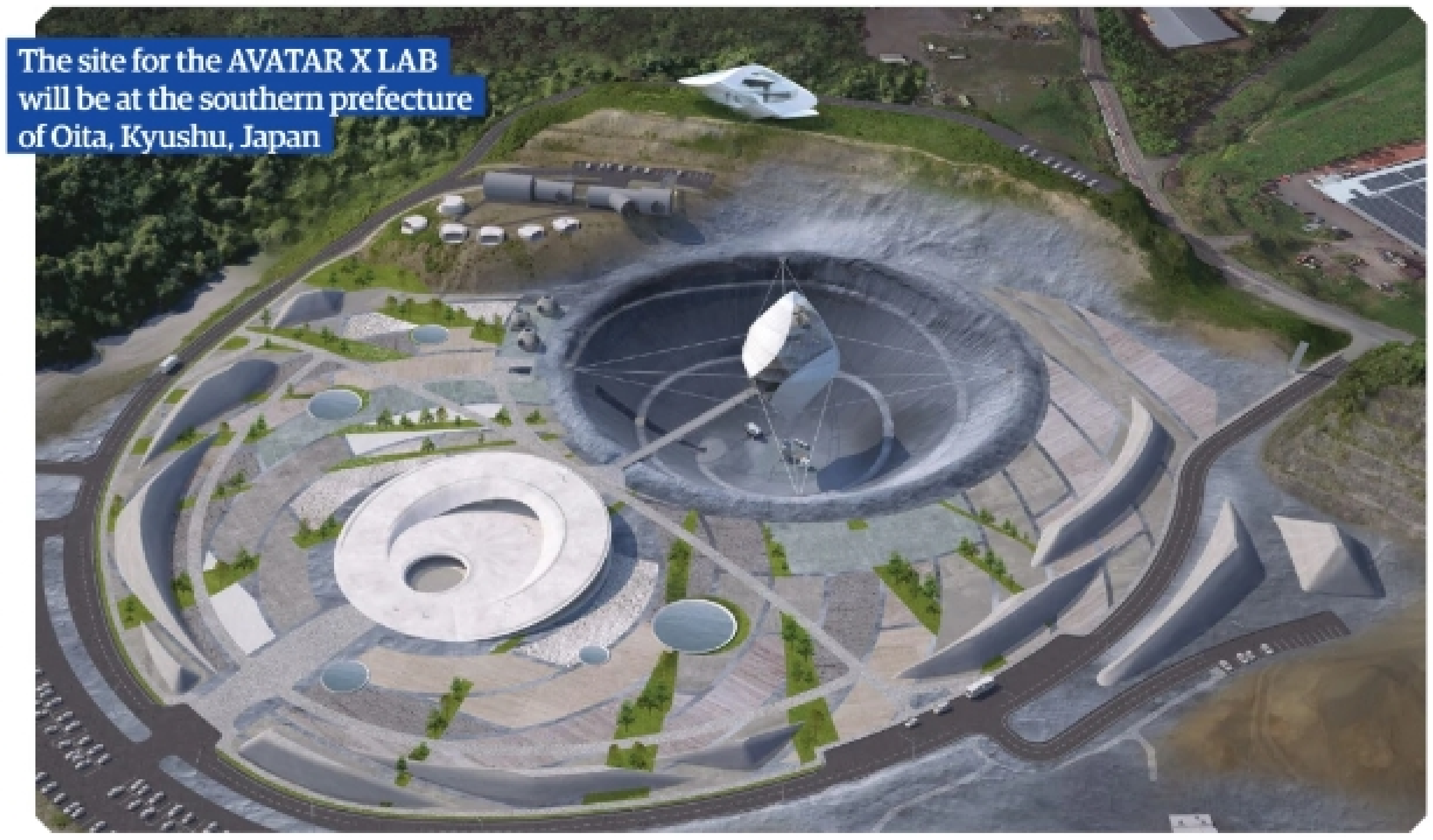
Building the base
The AVATAR X LAB @ OITA will be the base of Earth operations and research during this time. It will be the first-ever avatar space test field and will have an extremely unique design mimicking the feeling of being suspended in space and sitting above an artificial crater.

MOON, MARS AND BEYOND



To the Moon and beyond
Once in operation the aim of the programme is to use the exciting technologies on the Moon, Mars and beyond. This could be paramount in the erection of bases or important equipment, whether it be scientific or for any other space infrastructure.

The building will be suspended 18 metres (60 feet) above a crater



The site for the AVATAR X LAB will be at the southern prefecture of Oita, Kyushu, Japan

with a long list of names already signed up to the cause. With AVATAR X welcoming the help of different companies and organisations from all sectors that are interested in taking up the challenge of this pioneering space adventure, the consortium can be officially established. Once established the official forum can begin to discuss the plan of action and road map for the future of the AVATAR X program. This phase may take a few years, as collaboration is key, and gathering the organisations and collectively deciding on an agenda will take a fair amount of time - you can't build a great building on a weak foundation.

Once the consortium is decided on, the next step is to build the AVATAR X LAB @ OITA. This building will be the Earth-based haven of the AVATAR X operation. The site will be located in Japan's southern prefecture of Oita, Kyushu, and will be the world's first dedicated avatar space-test field. The building will be designed by the award-

© JAXA; Clouds Architecture Office; Adrian Mann

> "ANA is driven by a bold and inspiring vision of the future of flight, and this boldness doesn't stop on our planet"
>
> **Shinya Katanozaka**

winning architecture firm known as CLOUDS Architecture Office (CLOUDS AO). Preliminary designs of the lab are exquisite, and if constructed it will be a feat of architectural design with a unique idea to have a building held in suspension above a 'crater'. The reasoning behind this design is that it will embody the idea of 'being in the air' 18 metres (60 feet) above a moon-like crater, with the building accessible by a bridge.

This building will be home to the key telecommunication and research facilities that will enable testing for avatars in space scenarios. There will also be conference rooms, exhibition rooms, restaurants and other such amenities that will be available to the researchers and visitors that come and go. This level of creativity alone mirrors the task in hand for the AVATAR X program.

The third phase will occur in the early 2020s, and consists of taking the technologies created and developed at the AVATAR X LAB @ OITA and putting them into low-Earth orbit, which can be anywhere between 160 to 2,000 kilometres (99 to 1,243 miles) above the Earth's surface. This launch to low-Earth orbit will be used primarily for testing purposes, and tasks that can be performed in this region of space could potentially involve supporting astronauts on a space station, conducting scientific experiments and internal and external maintenance jobs. This could also be valuable in constructing, refuelling, servicing and repairing satellites and space probes in Earth orbit. Considering the ever-increasing population of satellites around Earth, to have robots in space 'doing the dirty work' would increase the lifetimes of many satellites.

MELTIN have already begun designs of what the avatars will look like, and have given it the name MELTANT-α. This long-distance remote-controlled robot will protect astronauts from the dangers of space while performing all the tasks needed. MELTIN have identified that in order to achieve the tasks that humans need to do, the robots have to have abilities close to that of a human. This is why they have designed MELTANT-α to have human-sized hands with the same speed, flexibility, power and haptics. Their fingers will allow for the same high-precision work that humans can perform.

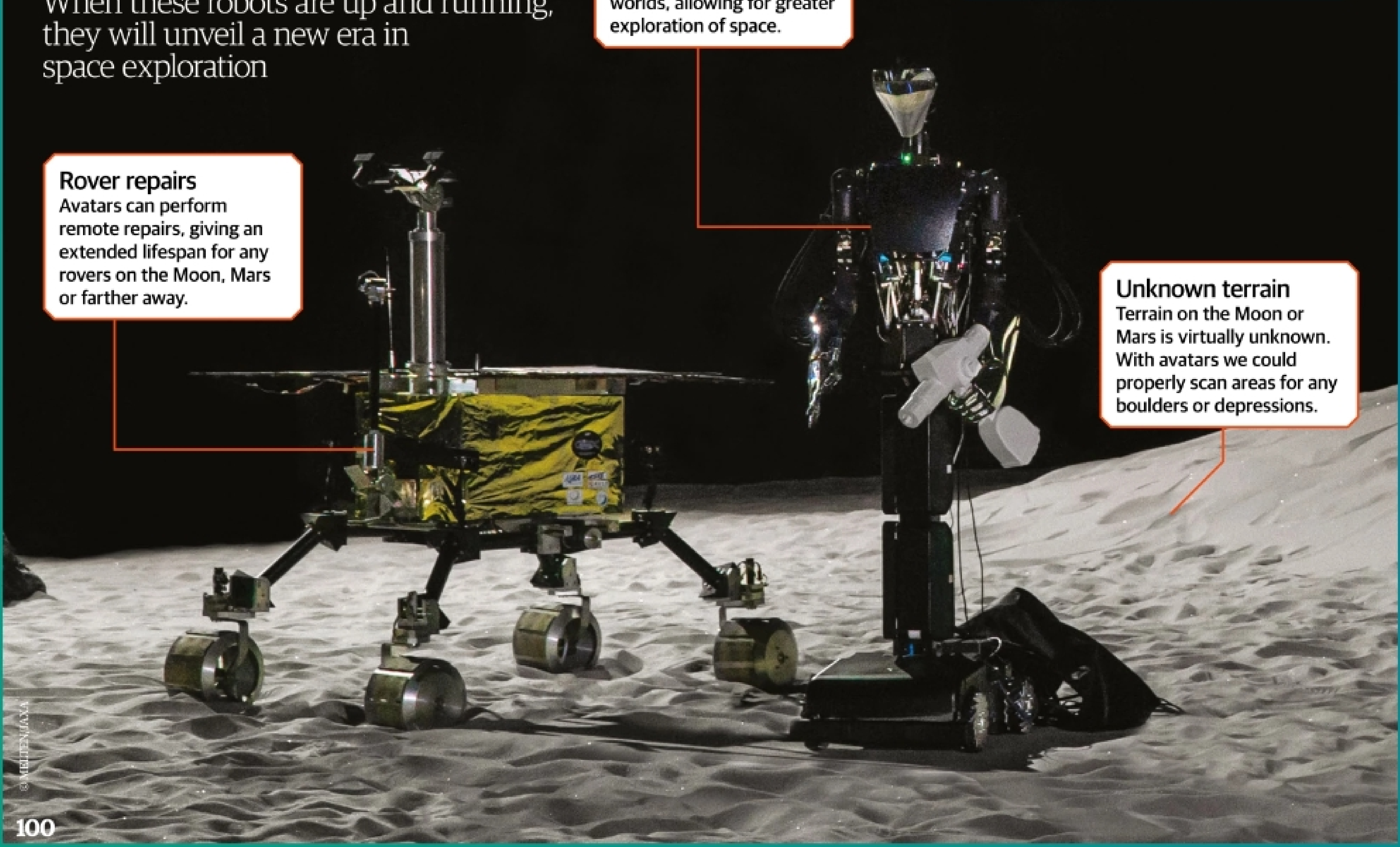
At this point, which is set for a time unknown, the fourth and final phase can take shape. The AVATAR X can finally be unleashed into the wilds of space and can begin with the building of bases, maintenance of rovers and other pieces of equipment, as well as providing valuable scientific data from afar. The most likely scenario is that the avatars will first be deployed on the Moon, hopefully venturing on to our neighbouring planet, Mars. This will not only be safer as opposed to using humans, it will be more cost effective and make several areas of space more accessible, all the while being controlled from the comfort of Earth.

"ANA is driven by a bold and inspiring vision of the future of flight, and this boldness doesn't stop on our planet," concludes Shinya Katanozaka, president and CEO of ANA. "Through innovative partnerships like AVATAR X, we are excited about the possibilities of what we can accomplish and where we can go when the private and public sectors join forces."

MELTANT-α will be remotely controlled by humans

Avatars touch down

When these robots are up and running, they will unveil a new era in space exploration



Human control
Human intelligence with robotic accessibility presents the best of both worlds, allowing for greater exploration of space.

Rover repairs
Avatars can perform remote repairs, giving an extended lifespan for any rovers on the Moon, Mars or farther away.

Unknown terrain
Terrain on the Moon or Mars is virtually unknown. With avatars we could properly scan areas for any boulders or depressions.

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INTRODUCING THE STARSHIP HOPPER

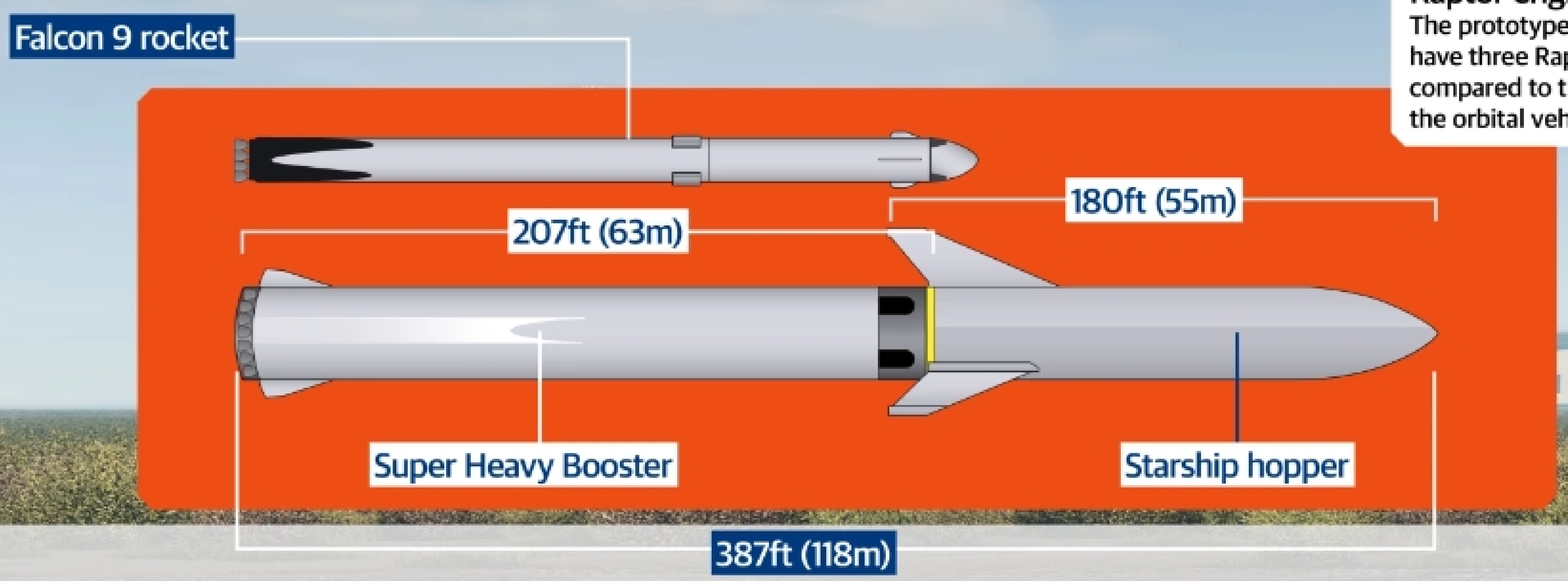
Elon Musk has teased the world with sneak peeks of what the spaceship to take humans to Mars could look like

Reported by Lee Cavendish

SpaceX continues to amaze in popularising space exploration. Not only is it doing fantastic work in reaching and exploring space, shown by its efforts to transport supplies and astronauts to the International Space Station, it also flaunts retro exhibitions that capture the interest of people worldwide. Recently, Elon Musk – the CEO of SpaceX – has released images and information on what he calls the 'Starship' Hopper test rocket. The prototype of this vehicle has recently been constructed in a project that will hopefully be used to colonise Mars.

Anyone who follows Musk will know that he is a keen advocate of going to Mars, and with scientists and engineers urging everyone to get behind an exploration mission that can take us to a whole new frontier, it is now becoming more of a reality than a dream. Starship, formerly known as the Big Falcon Rocket (BFR), could be the rocket to undertake this important task. In order for this rocket to be successful there are many things to take into account, and a lot of power needs to be exerted by the rocket. This is not just another 384,400-kilometre (238,855-mile) mission to the Moon. This is going to be a journey more than 140-times longer. This means that there needs to be enough food, supplies and protection from the harmful radiation of space in order to survive this journey, and even then there's the question of how much fuel is needed to break free of Earth's gravity and make it Mars.

These are the reasons why a voyage to Mars is a struggle. But nothing good ever comes easy. SpaceX has shown extremely promising signs of improved space exploration with the introduction of reusable rockets, and now Musk has released the first images of the Starship prototype rocket that will soon undergo short 'hopping' excursions to test its feasibility. These vertical takeoff and landing (VTOL) tests will hover around five kilometres (three miles) above the ground before landing back on Earth. The rocket towers at a height of about 39 metres (128 feet) and has a diameter of nine metres (30 feet),



Raptor engines
The prototype Hopper will have three Raptor engines, compared to the seven for the orbital vehicle.

> "Starship will be just one part of the entire project - SpaceX is also developing the Super Heavy rocket which will give Starship the initial thrust"

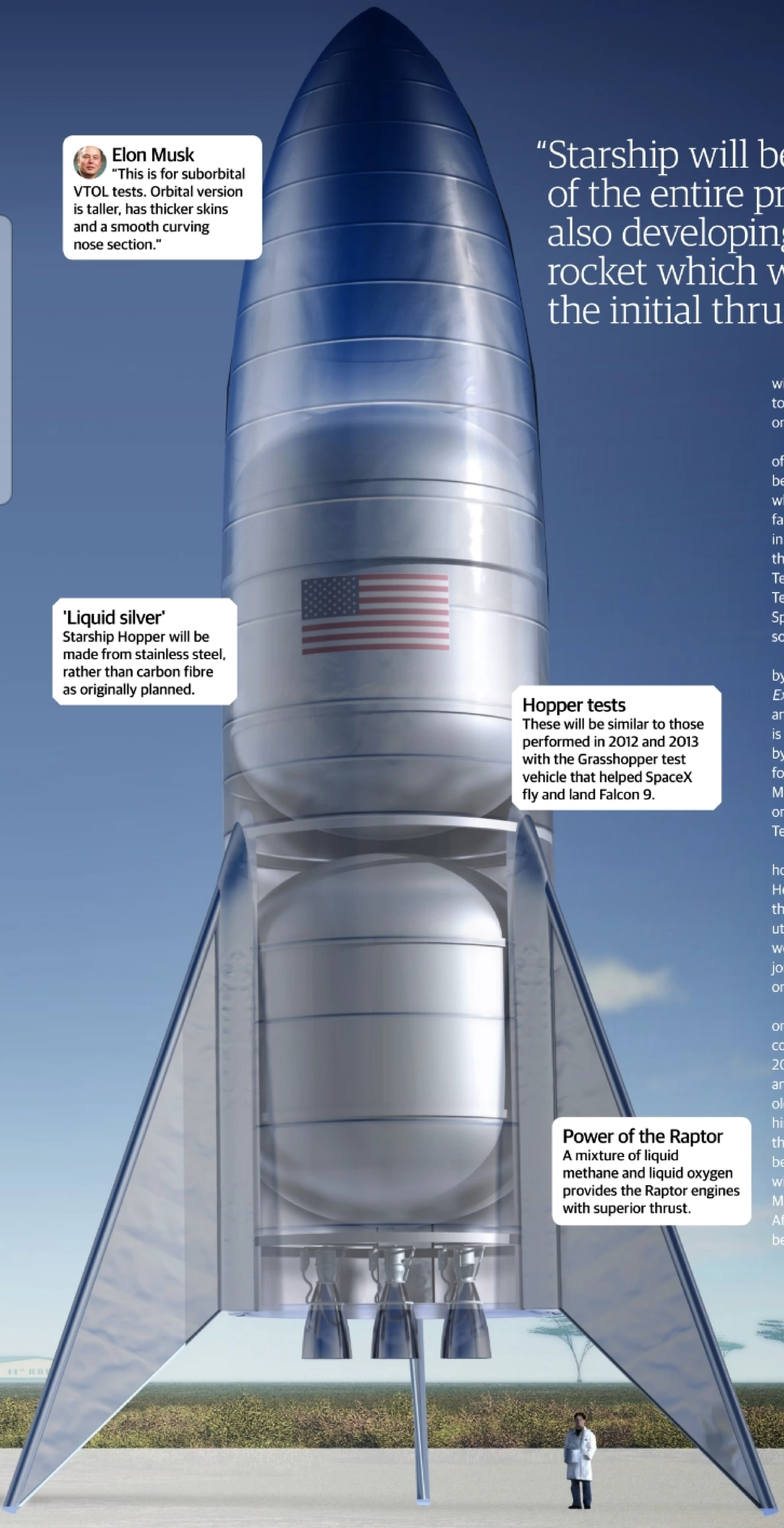
with a stainless-steel exterior starting at its pointy tip to its three rear 'fins' that serve as its legs as it stands on the ground.

The Starship looks strikingly like something out of a 1950s science-fiction comic book, and that's because it was modelled after one. Again, anyone who follows Musk will also know that he is a huge fan of cultural references in his SpaceX work. Back in February 2018 Musk tested the Falcon Heavy, in the process launching one of his sister company's Tesla cars into an orbit around the Sun. Inside the Tesla was Starman, a human-scale mannequin with SpaceX's spacesuit, given its name after the 1972 hit song by David Bowie.

In the case of Starship, the rocket was inspired by the 1954 adventure of comic-book hero Tintin in *Explorers of Space*. Although it doesn't have the red-and-white chequered appearance, everything else is remarkably similar. This inspiration was confirmed by Musk at an event in September 2018 at which he followed up by saying: "If in doubt, go with Tintin." Musk tweeted a picture of the prototype sitting at one of SpaceX's factories near Boca Chica Village in Texas, United States.

Starship will be just one part of the entire project, however, as SpaceX is also developing the Super Heavy rocket which will give Starship the initial thrust to escape Earth's gravity. The Super Heavy will utilise the powerful Raptor engine that SpaceX is still working on. In September 2019 SpaceX completed joining the bottom and top halves of the Starship orbital-scale prototype for improved testing.

This project is sure to be an extremely exciting one to follow as Musk has outlined his ambitions to conduct two unmanned cargo missions to Mars by 2022, followed by a crewed trip around the Moon and back as early as 2023 which will carry 43-year-old Japanese billionaire Yusaku Maezawa and make him the world's first private astronaut, ushering in the era of space tourism. Then, by 2024, SpaceX will be ready to conduct crewed missions to Mars. This will provide the platform for creating settlements on Mars, and science fiction will become a firm reality. After that, the possibilities are endless. Could Mars be the answer to problems on Earth?



Elon Musk
"This is for suborbital VTOL tests. Orbital version is taller, has thicker skins and a smooth curving nose section."

'Liquid silver'
Starship Hopper will be made from stainless steel, rather than carbon fibre as originally planned.

Hopper tests
These will be similar to those performed in 2012 and 2013 with the Grasshopper test vehicle that helped SpaceX fly and land Falcon 9.

Power of the Raptor
A mixture of liquid methane and liquid oxygen provides the Raptor engines with superior thrust.

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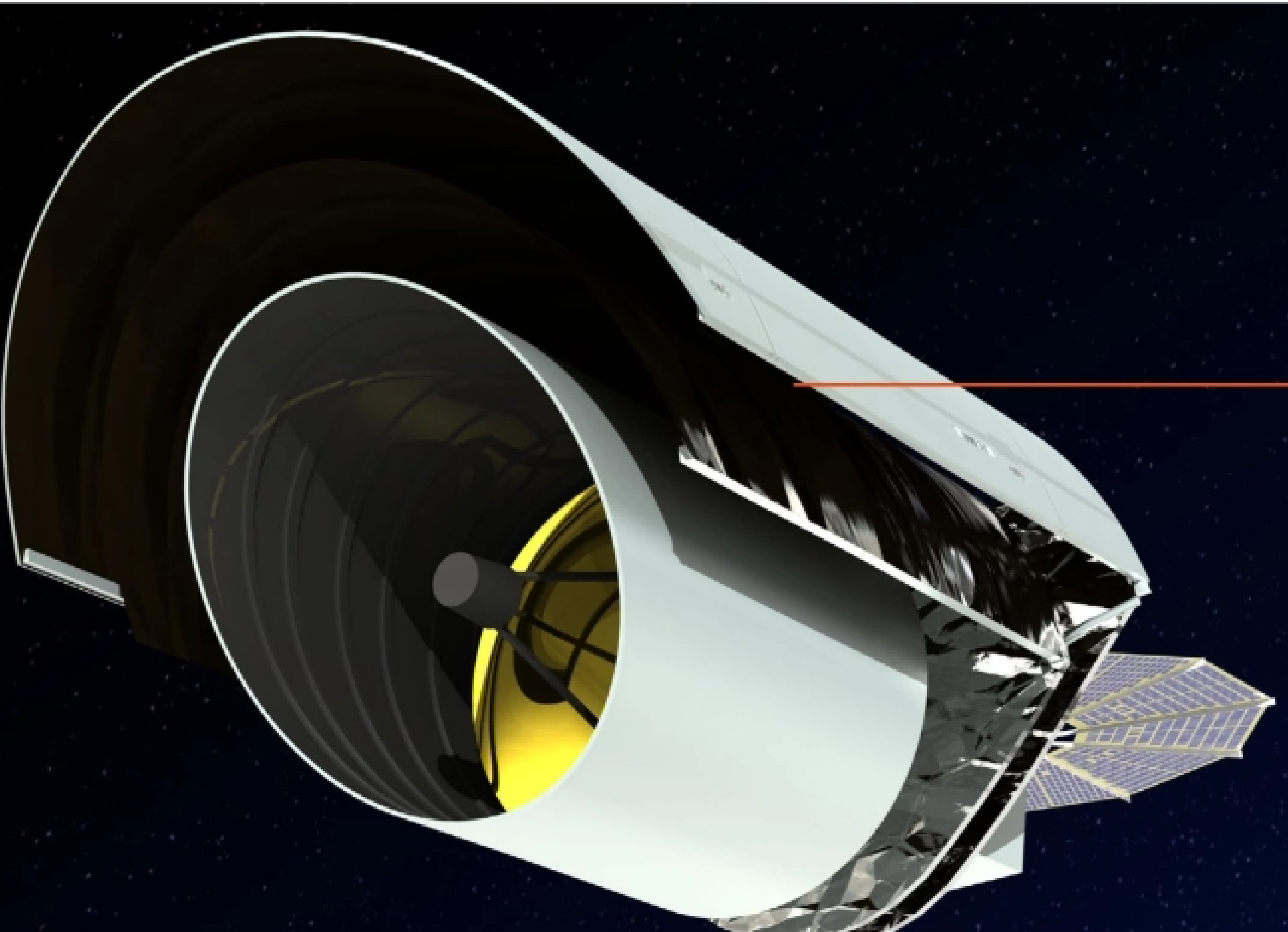


THE NEXT GENERATION OF SPACE TELESCOPES

Take a look at NASA's great observatories of the future

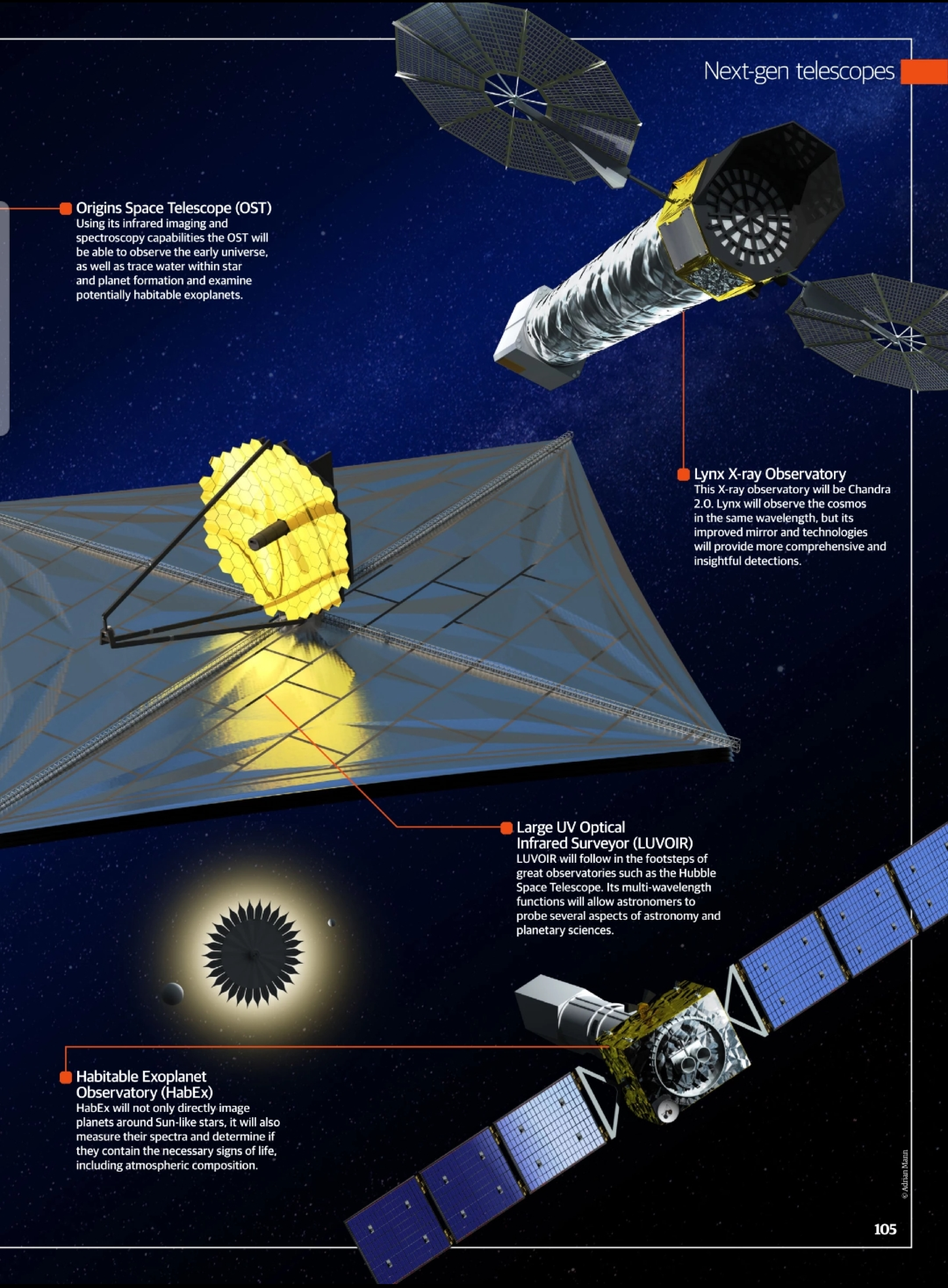
Although NASA have yet to launch the James Webb Space Telescope (JWST), now scheduled to launch in March 2021, they have already started planning for a better telescope to become its successor. At the 233rd meeting of the American Astronomical Society (AAS) in Seattle, Washington, US, four mission-concept studies were presented to show the future of space telescopes. But of these four, only one will launch in the mid-2030s.

These proposed missions will explore the universe in a range of wavelengths that will reveal incredible details about exoplanets, galaxies, black holes, stars and even objects in our own Solar System. NASA has yet to put any price tags on these missions due to their preliminary status, but these type of flagship-class missions typically cost over $1 billion (£771 million) – the JWST is estimated to cost over $10 billion (£7.7 billion). One of the missions will look at the far-infrared universe and peer into the dust clouds that are scattered across space in order to investigate how stars and planets are formed. This telescope, the Origins Space Telescope (OST), will be 15 metres (50 feet) in diameter, which is four-times the size of the European Space Agency's Herschel Space Observatory.

Another mission will look at potentially habitable exoplanets around Sun-like stars at wavelengths from near-infrared to ultraviolet. The Habitable Exoplanet Observatory, or HabEx, will deploy a large, sunflower-shaped starshade that will block the light of the star in order to directly observe the orbiting exoplanet, much like how a coronagraph blocks out the Sun's light to observe the corona. The telescope itself will have a mirror diameter of four metres (13 feet), with the starshade stretching out to a much larger 72 metres (236 feet).

Another candidate is the Large UV Optical Infrared Surveyor (LUVOIR). As its name suggests it will look to observe the universe in multiple wavelengths. Think of it as a new-and-improved Hubble Space Telescope. This telescope, with a mirror diameter six-times that of Hubble's, will be able to stare into the early stages of the universe. By being able to study the first galaxies and the reionisation period that took place not long after the Big Bang, our evolution throughout time and space will become more apparent.

Last but not least is the Lynx X-ray Observatory, the potential successor to NASA's Chandra X-ray Observatory. It has the potential to be two orders of magnitude higher in sensitivity than Chandra as it looks at the most energetic events to occur throughout the cosmos, such as black holes from the earliest galaxies and newly born stars. To put that into perspective, Chandra can study stars as far away as 1,300 light years, but with Lynx that figure will increase up to 16,000 light years – over 12-times farther!



Origins Space Telescope (OST)
Using its infrared imaging and spectroscopy capabilities the OST will be able to observe the early universe, as well as trace water within star and planet formation and examine potentially habitable exoplanets.

Lynx X-ray Observatory
This X-ray observatory will be Chandra 2.0. Lynx will observe the cosmos in the same wavelength, but its improved mirror and technologies will provide more comprehensive and insightful detections.

Large UV Optical Infrared Surveyor (LUVOIR)
LUVOIR will follow in the footsteps of great observatories such as the Hubble Space Telescope. Its multi-wavelength functions will allow astronomers to probe several aspects of astronomy and planetary sciences.

Habitable Exoplanet Observatory (HabEx)
HabEx will not only directly image planets around Sun-like stars, it will also measure their spectra and determine if they contain the necessary signs of life, including atmospheric composition.

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Manned spacecraft
Astronauts will be transported to and from the CSS by the Shenzhou spacecraft, which roughly translates to 'divine vessel'. This vessel has been taking astronauts to space since 2003.

CHINA'S NEXT SPACE STATION

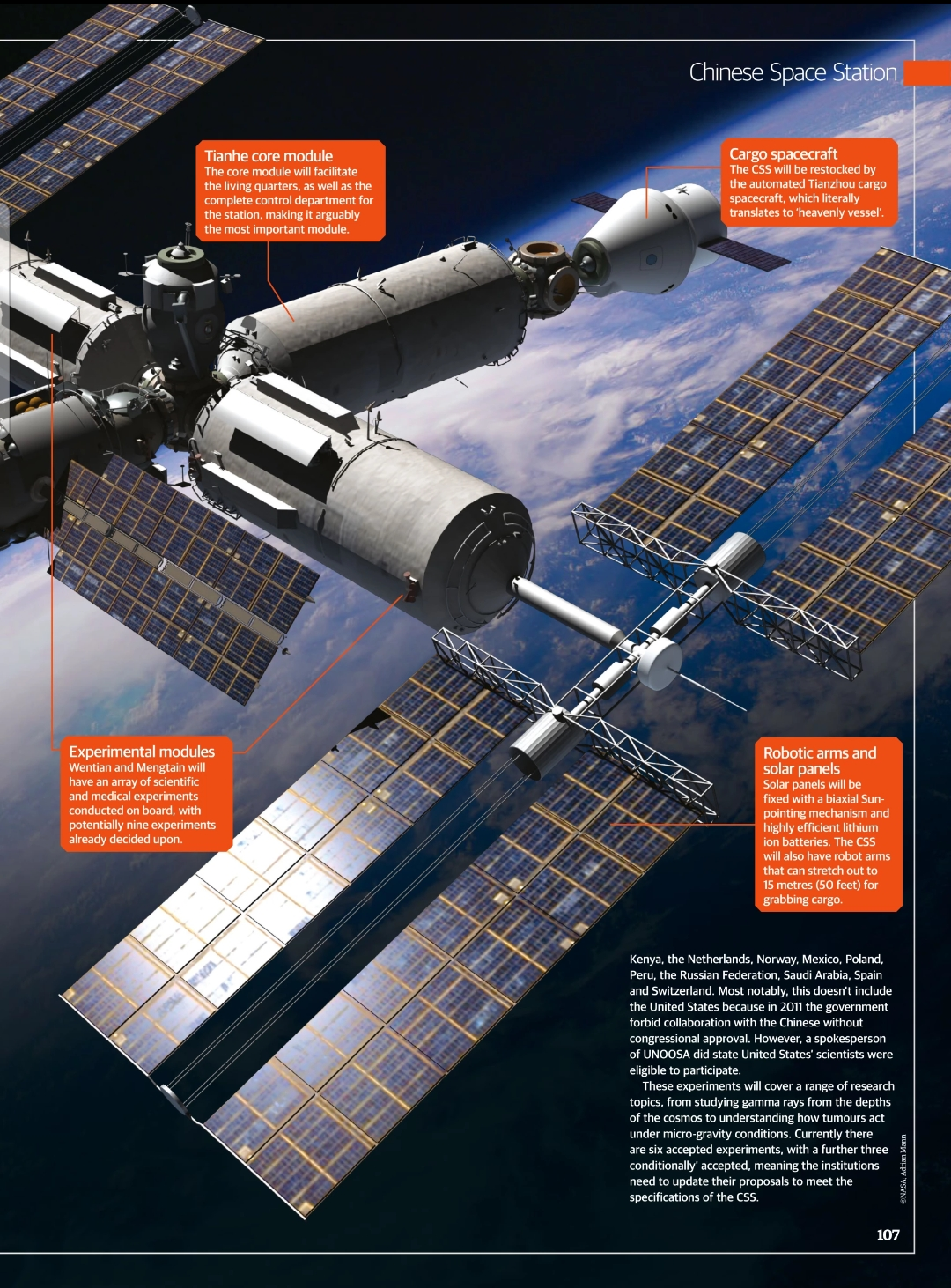
Low-Earth orbit construction will hopefully begin in 2020, where it will eventually accommodate three astronauts

There have been many successful space stations throughout the years: NASA's Skylab, Russia's Mir space station and the collaborative International Space Station (ISS), built between the space agencies of Canada, Europe, Japan, Russia and the US. China is another country to have established its presence in low-Earth orbit with space stations Tiangong-1 and Tiangong-2. Now, with 2020 not far off, China is preparing for its next space outpost, which will be known as the Chinese Space Station (CSS).

Tiangong-2 was launched into space in 2016 and dropped out of orbit on 19 July 2019, but this space station was created with the main purpose of testing key technologies for the CSS. The CSS will be around 60 tonnes (130,000 pounds), which is roughly a seventh of the weight of the ISS and roughly half the weight of Russia's Mir space station. This new space station will consist of a core module called 'Tianhe' – meaning 'harmony of the heavens' in Mandarin – two experimental modules, 'Wentain' and 'Mengtian', translating to 'quest for the heavens' and 'dreaming of the heavens' respectively, a cargo spacecraft, a manned spacecraft and several solar panels.

The core module is the centrepiece of the space station. The 18-metre (60-foot) long module with a maximum diameter of 4.2 metres (14 feet) will be the first piece of the puzzle launched into space. It will be sent up around 2020 by China's own heavy-duty rocket, the Long March 5. However, this is dependant on how test flights of the rocket go in late 2019. If all goes to plan then the core module will reach low-Earth orbit and provide three astronauts with their accommodation suite as well as housing vital navigation, guidance, orientation, power, propulsion and life systems for the entire station.

The two experimental modules will be next, and in June 2019 the United Nations Office for Outer Space Affairs (UNOOSA) and the China Manned Space Agency (CMSA) announced the six winning experiments that will be conducted on board the CSS when construction is finished – in 2022 if all goes to plan. These experiments promote international cooperation as the winning institutions come from all over the globe, with science from Belgium, China, France, Germany, India, Italy, Japan,



Tianhe core module
The core module will facilitate the living quarters, as well as the complete control department for the station, making it arguably the most important module.

Cargo spacecraft
The CSS will be restocked by the automated Tianzhou cargo spacecraft, which literally translates to 'heavenly vessel'.

Experimental modules
Wentian and Mengtain will have an array of scientific and medical experiments conducted on board, with potentially nine experiments already decided upon.

Robotic arms and solar panels
Solar panels will be fixed with a biaxial Sun-pointing mechanism and highly efficient lithium ion batteries. The CSS will also have robot arms that can stretch out to 15 metres (50 feet) for grabbing cargo.

Kenya, the Netherlands, Norway, Mexico, Poland, Peru, the Russian Federation, Saudi Arabia, Spain and Switzerland. Most notably, this doesn't include the United States because in 2011 the government forbid collaboration with the Chinese without congressional approval. However, a spokesperson of UNOOSA did state United States' scientists were eligible to participate.

These experiments will cover a range of research topics, from studying gamma rays from the depths of the cosmos to understanding how tumours act under micro-gravity conditions. Currently there are six accepted experiments, with a further three 'conditionally' accepted, meaning the institutions need to update their proposals to meet the specifications of the CSS.

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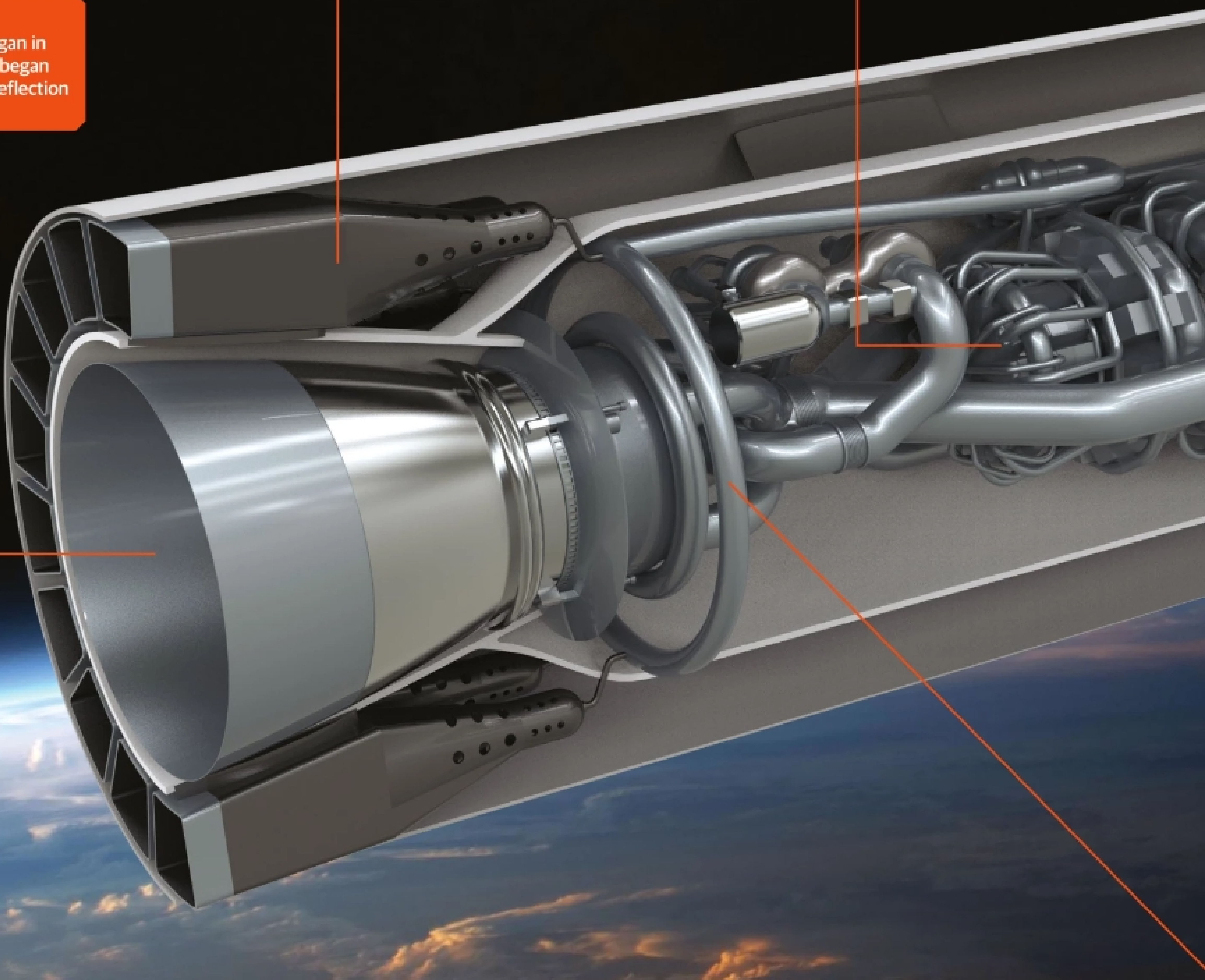


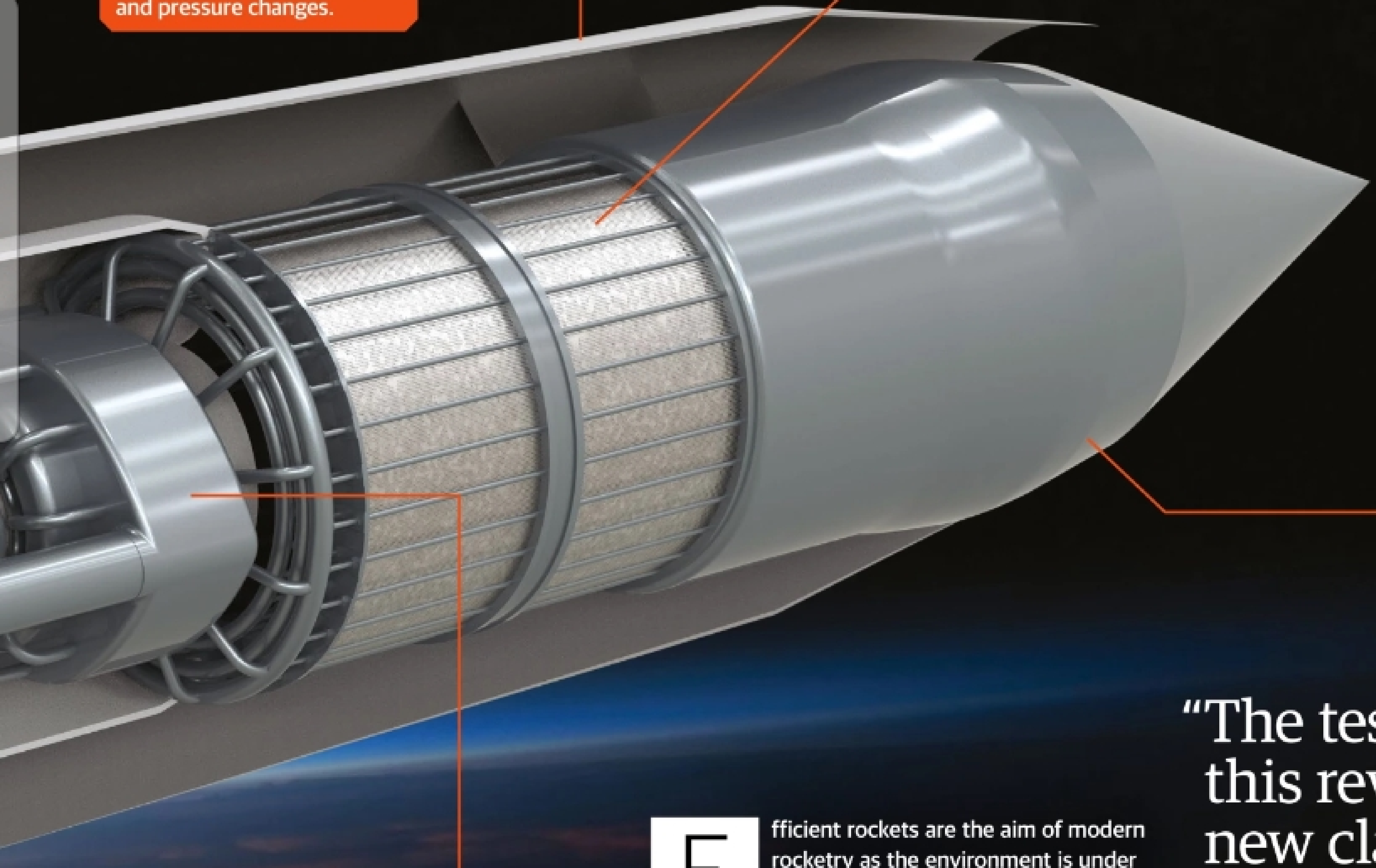
Ramjet
The ramjet soaks in the intake air leftover from the air-breathing propulsion system.

Turbine
A gas turbine, running on a helium hoop recycling system, powers the turbo-compressor.

Nozzle
Trials for the nozzle began in 2008 when engineers began testing an expansion deflection nozzle called STERN.

THE SABRE ROCKET

A joint ESA and UKSA engine that's able to breathe air is set to revolutionise spaceflight as we know it



Nacelle
The rocket's housing must be sturdy enough to keep everything in place and deal with the rapid temperature and pressure changes.

Pre-cooler
The hot intake air must be cooled and made suitable to power the rocket.

Supersonic air intake
The rocket requires the intake of air when travelling over three-times the speed of sound.

Compressor
The turbo-compressor powers the jet-engine stage of the rocket.

Rocket engine
After the rocket has passed five-times the speed of sound, the liquid-propellant rocket engine stage is ignited.

Efficient rockets are the aim of modern rocketry as the environment is under threat. The price of fuel is constantly on the rise due to a lack of resources, and this could be the answer: the first air-breathing rocket. Recently the European Space Agency (ESA) and the United Kingdom Space Agency (UKSA) have green-lit the next major series of tests for Reaction Engine Limited's SABRE.

SABRE is an acronym for 'Synergetic Air Breathing Rocket Engine', planned to be able to utilise atmospheric air during the initial 25 kilometres (16 miles) of the rocket's ascent. During this period a SABRE rocket could travel up to five-times the speed of sound, after which point it would switch to the pure-rocket mode to make the final climb into sub-orbital spaceflight.

ESA and the UKSA have invested a lot of time and money into the SABRE project in the past, with UKSA investing £50 million (approximately $63 million) and the ESA a further £8.9 million (around $11 million). "The positive conclusion of our preliminary design review marks a major milestone in SABRE development," comments Mark Ford, heading ESA's propulsion engineering section. "It confirms the test version of this revolutionary new class of engine is ready for implementation."

The SABRE rocket can be broken down into three sections: the pre-cooler front, the encore engine and the thruster chamber at the rear. The thruster chamber is the same iconic region as on any modern rocket that applies the thrust, but the core is what has been extensively examined by ESA and UKSA in their aforementioned tests. The core has to be capable of withstanding the pressures of both rocket and jet-engine capabilities as it shifts between air-breathing and rocket-engine modes.

> "The test version of this revolutionary new class of engine is ready for implementation"

The pre-cooler is also a pivotal part of SABRE. As its name suggests it cools the air it ingests in order to fuel the rocket in its air-breathing phase. As the air becomes thinner at high altitudes there is less jet fuel, hence why SABRE must then revert to rocket fuel. The pre-cooler has to be able to tame air that is coming in at high temperatures because of the supersonic – and even hypersonic – speeds. The most recent pre-cooler tests have proven very encouraging as it managed to rapidly quench airflow that was coming in at 420 degrees Celsius (788 degrees Fahrenheit) in a 20th of a second.

By creating a hybrid between the two aeronautic engines the rocket can save on the amount of fuel it needs to take, therefore reducing the mass of the payload. This has promising aspects not only for suborbital spaceflight, but also intercontinental supersonic travel, theoretically taking passengers from London to Australia in just 4.5 hours.

"As the home of the jet engine, the UK has a rich aerospace heritage and world-renowned skills and expertise," says Chris Castelli, director of programmes at UKSA. "This is an exciting landmark for Reaction Engines in the development of its SABRE engine, which could revolutionise both access to space and international travel by powering aircraft to five-times the speed of sound."

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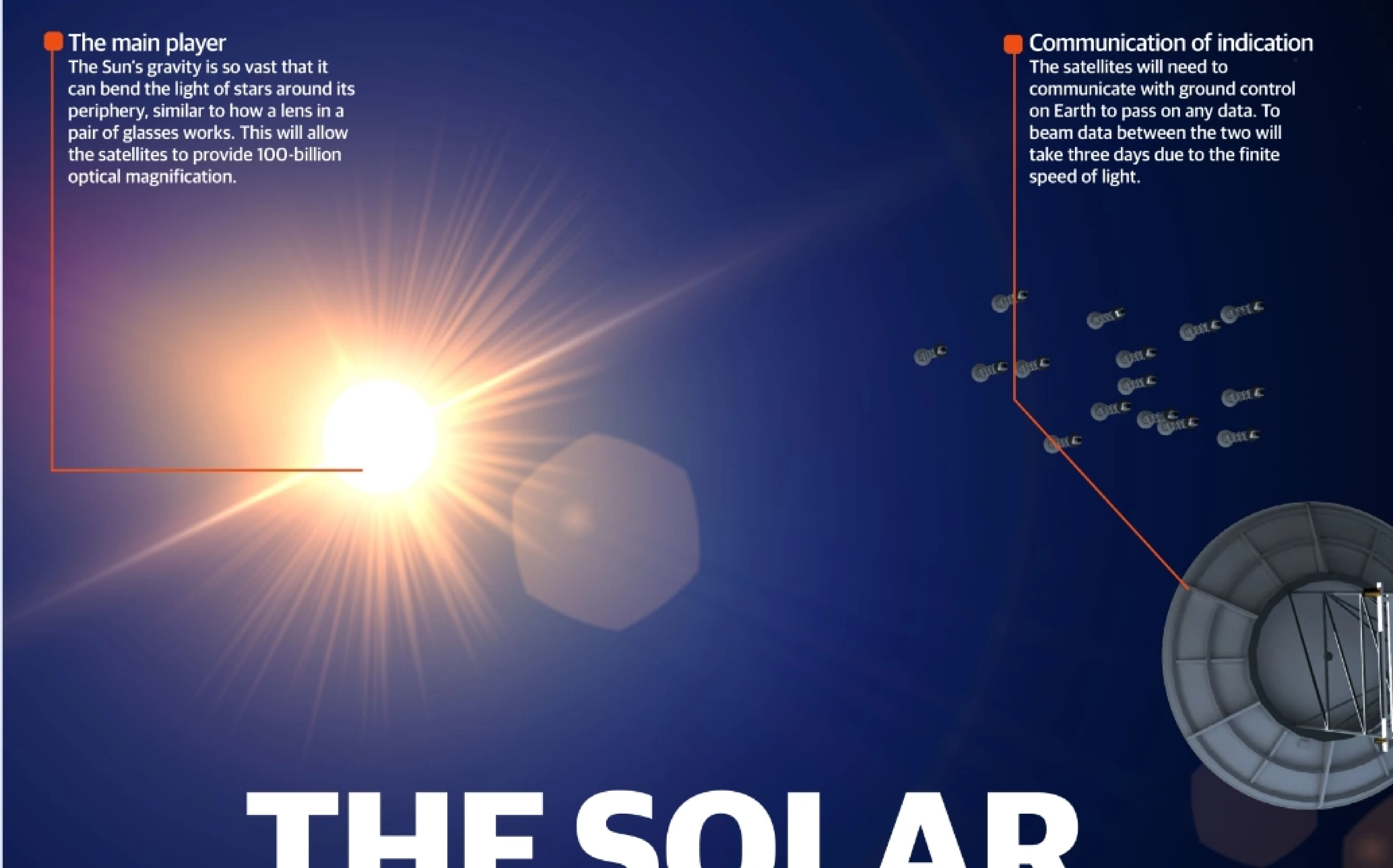


The main player
The Sun's gravity is so vast that it can bend the light of stars around its periphery, similar to how a lens in a pair of glasses works. This will allow the satellites to provide 100-billion optical magnification.

Communication of indication
The satellites will need to communicate with ground control on Earth to pass on any data. To beam data between the two will take three days due to the finite speed of light.

THE SOLAR GRAVITY LENS

A swarm of telescopes placed billions of kilometres away will be able to reveal a universe full of exoplanets

The search for exoplanets is a relatively new and exciting aspect of study, and finding Earth 2.0 is a goal that astronomers hope to achieve by using innovative methods of detection. Based on Einstein's theory of general relativity which predicted that the most massive objects in the universe can warp the space around them and can bend light, a process known as gravitational lensing, it is possible to concentrate distant light to allow for a closer look.

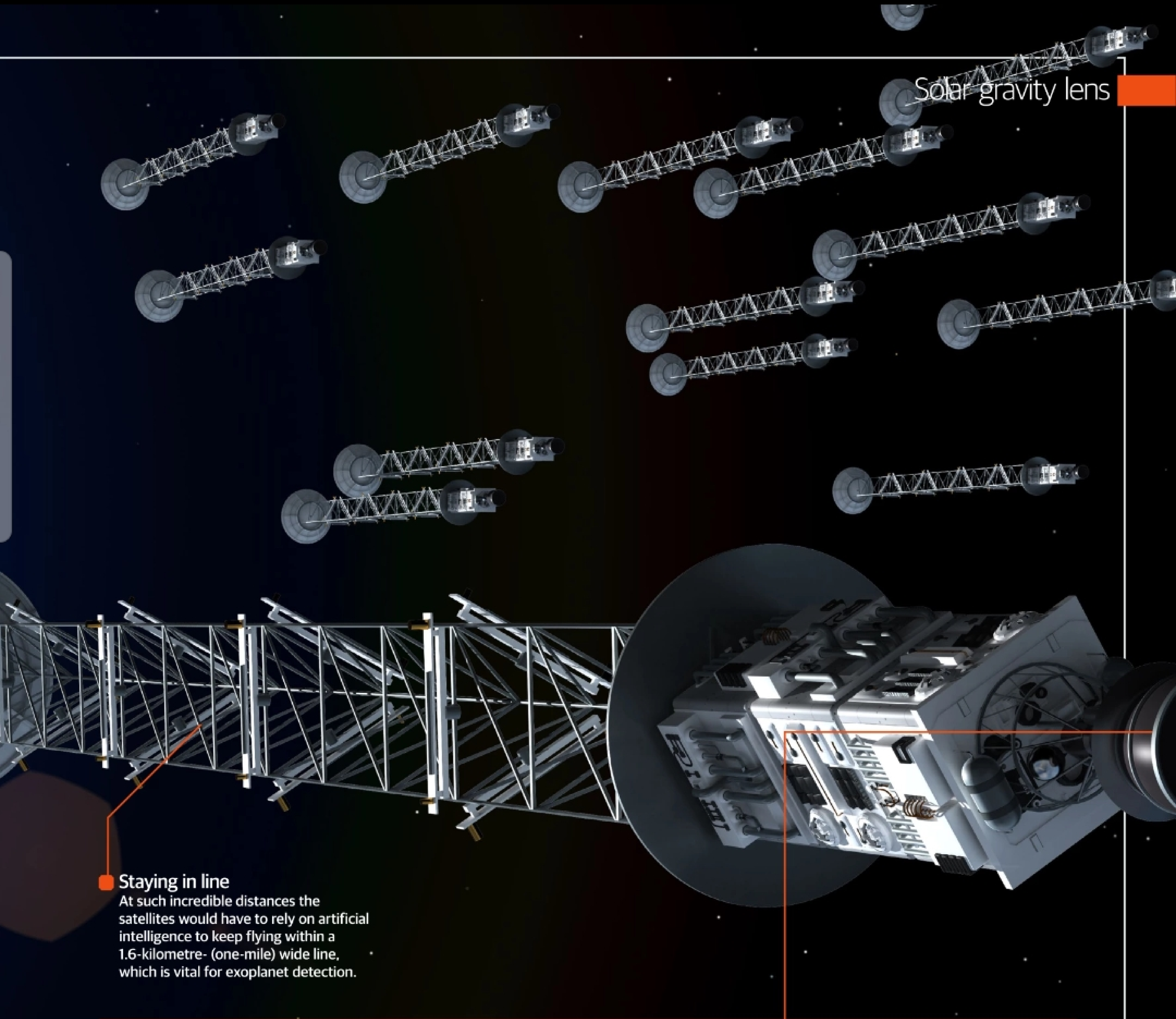
This century-old theory has led to the development of the solar gravity lens (SGL) method of exoplanet detection, courtesy of scientists from NASA's Jet Propulsion Laboratory and The Aerospace Corporation. This two-year study was made possible when Aerospace was awarded a $130,000 contract from JPL as part of the NASA Innovative Advanced Concepts (NIAC) Phase II program.

"SGL requires placement of an array of detectors that observe the light from exoplanets once they arrive at a distance approximately 50 billion miles [80.5 billion kilometres] or 550 astronomical units (AU) from Earth," says Tom Heinsheimer, Aerospace's technical co-lead for SGL. "To get to that solar gravity line the swarm of spacecraft will need to use a solar sail to fly out of the Solar System at a velocity of over 75 miles [121 kilometres] per second." One AU is the Earth-Sun distance, meaning the distance of this focal 'ring' would be three light days away.

By placing a system of telescopes over 80 billion kilometres (50 billion miles) from Earth the SGL will provide an outstanding magnification of 100 billion. This level of magnification will reveal details as small as 10-kilometres (six-miles) across – the equivalent of spotting New York City on an exoplanet. This grand scale of telescopes would undeniably tackle exoplanet detection in a pioneering fashion, but there are problems to tackle before doing so – the main one being having to send a swarm of satellites such an enormous distance from Earth.

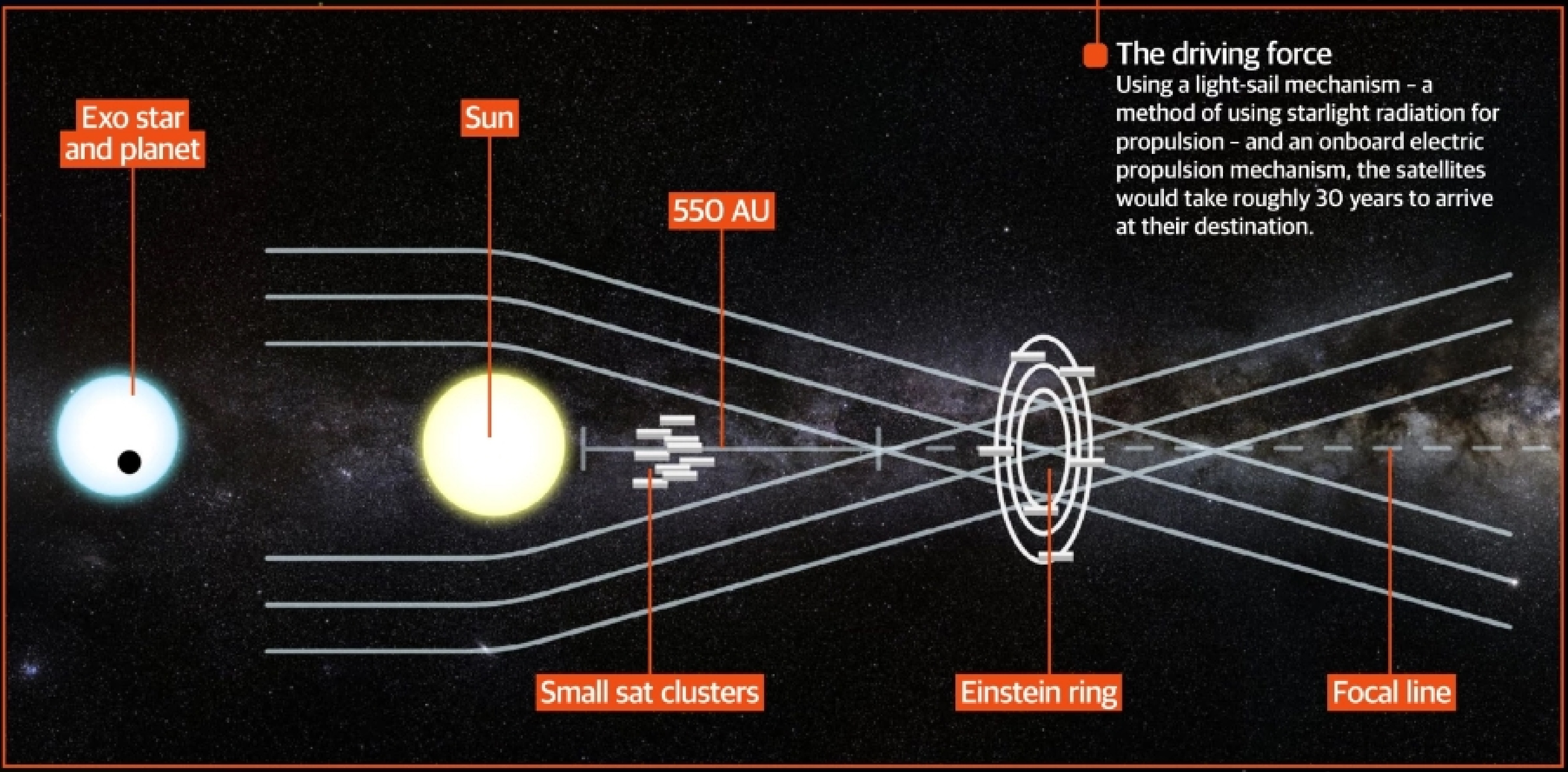
When considering the farthest human-made object, NASA's Voyager 1 currently holds that record at 145 AU from Earth – and that has taken over 40 years! This long time span is only because the spacecraft was restricted by the technologies of its time. With the new proposed propulsion and light-sail concept the cluster of small telescopes will take roughly 30 years to get to a distance of 550 AU.

The navigation and propulsion will require some form of artificial intelligence, as technologies will need to keep the spacecraft flying in a 1.6-kilometre- (one-mile) wide line that will contain the light from the exoplanet. As this round trip of communication with Earth would take six days it is imperative that this swarm can adapt and learn from experience.



Staying in line
At such incredible distances the satellites would have to rely on artificial intelligence to keep flying within a 1.6-kilometre- (one-mile) wide line, which is vital for exoplanet detection.

The driving force
Using a light-sail mechanism – a method of using starlight radiation for propulsion – and an onboard electric propulsion mechanism, the satellites would take roughly 30 years to arrive at their destination.



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Solar System

Discover the secrets of our fascinating planetary system

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Astronomers are beginning to understand how the ice giant came to be the weirdest planet in the Solar System

122 Our Sun is getting hotter
As our nearest star enters its next solar cycle, physicists have revealed what the future holds – and it's not what they expected

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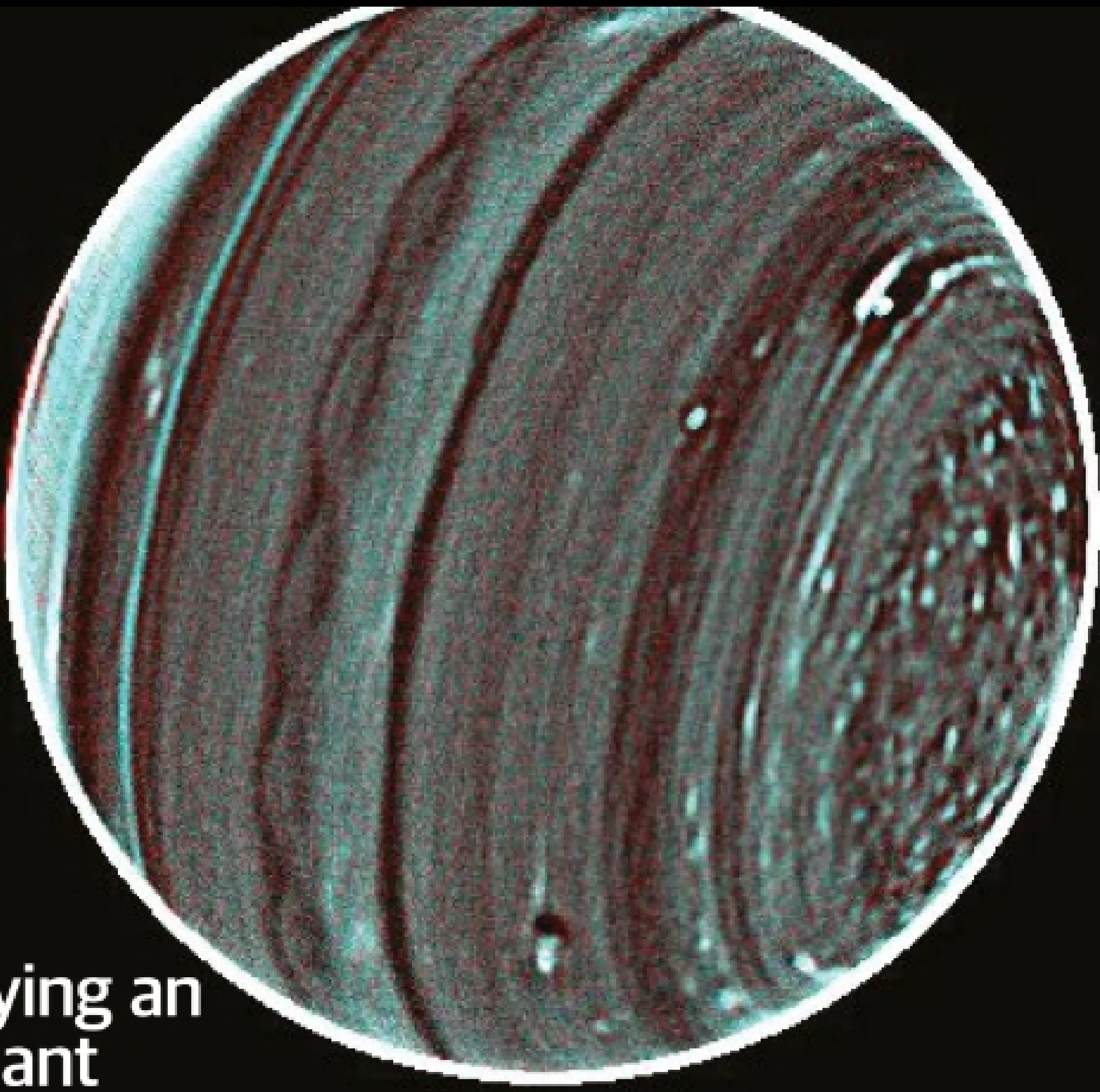
Could this hidden planet really exist? All About Space meets the scientists who could be on the trail of an undiscovered world

> “We need to figure out if our understanding of Uranus would benefit from a dedicated mission”



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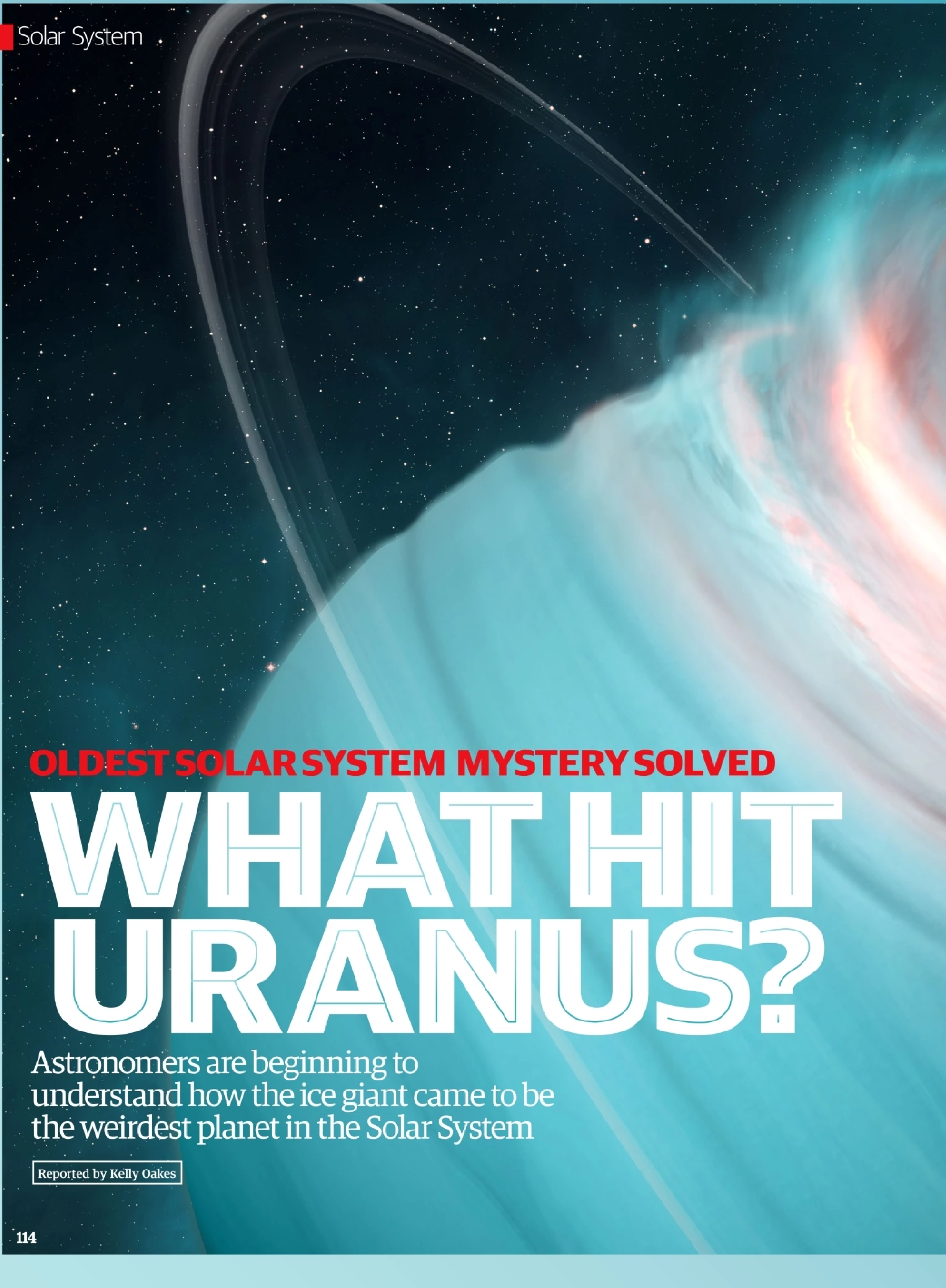


OLDEST SOLAR SYSTEM MYSTERY SOLVED

WHAT HIT URANUS?

Astronomers are beginning to understand how the ice giant came to be the weirdest planet in the Solar System

Reported by Kelly Oakes

The eight major planets in our Solar System are all mysterious in their own ways, but Uranus, seventh from the Sun, is particularly weird. The ice giant is tilted, its north and south poles where you would expect the planet's equator to be. Its magnetic field is off-centre. And though you'd expect an ice giant to be cold, Uranus is even colder than scientists think it should be. Now researchers are starting to unravel how it came to be this way.

Just like Saturn and Neptune, Uranus has a ring system. However, because the planet is tilted 98 degrees, its rings orbit the ice giant vertically instead of around its middle – for comparison, Earth is tilted 23 degrees, and Jupiter a mere three degrees. It also has plenty of moons, including five major ones and at least 22 other known satellites, which orbit the same way.

Aside from the moons and rings, Uranus' tilt also dramatically affects the conditions on the planet itself. The length of a day on Uranus changes a lot over the ice giant's orbit around the Sun. Each pole of Uranus spends around 42 Earth years pointing towards the Sun, while the other faces away, before they switch.

When one of the planet's poles is most directly pointing towards the Sun, called a solstice, only a small part of the planet near the equator experiences a day-night cycle, while that pole is bathed in light and the other in dark. As it orbits the Sun the planet gradually spins until eventually the other pole faces the Sun. In the middle, at the planet's equinoxes, the equator of the planet faces

> "Aside from the moons and the rings, Uranus' tilt also dramatically affects the conditions on the planet itself"

the Sun, and its day-night cycles are more similar to what we are used to on Earth.

The planet itself looks pretty blank and featureless from a distance. When the Voyager 2 spacecraft came within 81,500 kilometres (50,600 miles) of the top of Uranus' atmosphere in January 1986 – the only time we have visited the planet – it saw a smooth, turquoise expanse. But this calm exterior belies stranger things underneath.

The planet's atmosphere is mostly made up of hydrogen, helium and methane, with some other hydrocarbons, too. The methane is what gives the planet its bluish-green hue, because the gas absorbs red wavelengths of light. Though it looks calm, the Hubble Space Telescope revealed that Uranus has an active weather system with strong winds, bright clouds and even aurorae. "It's very hard to see them because the exterior is so boring; it's hard to tell what's going on," says Jacob Kegerreis, a PhD student in computational astrophysics at the University of Durham.

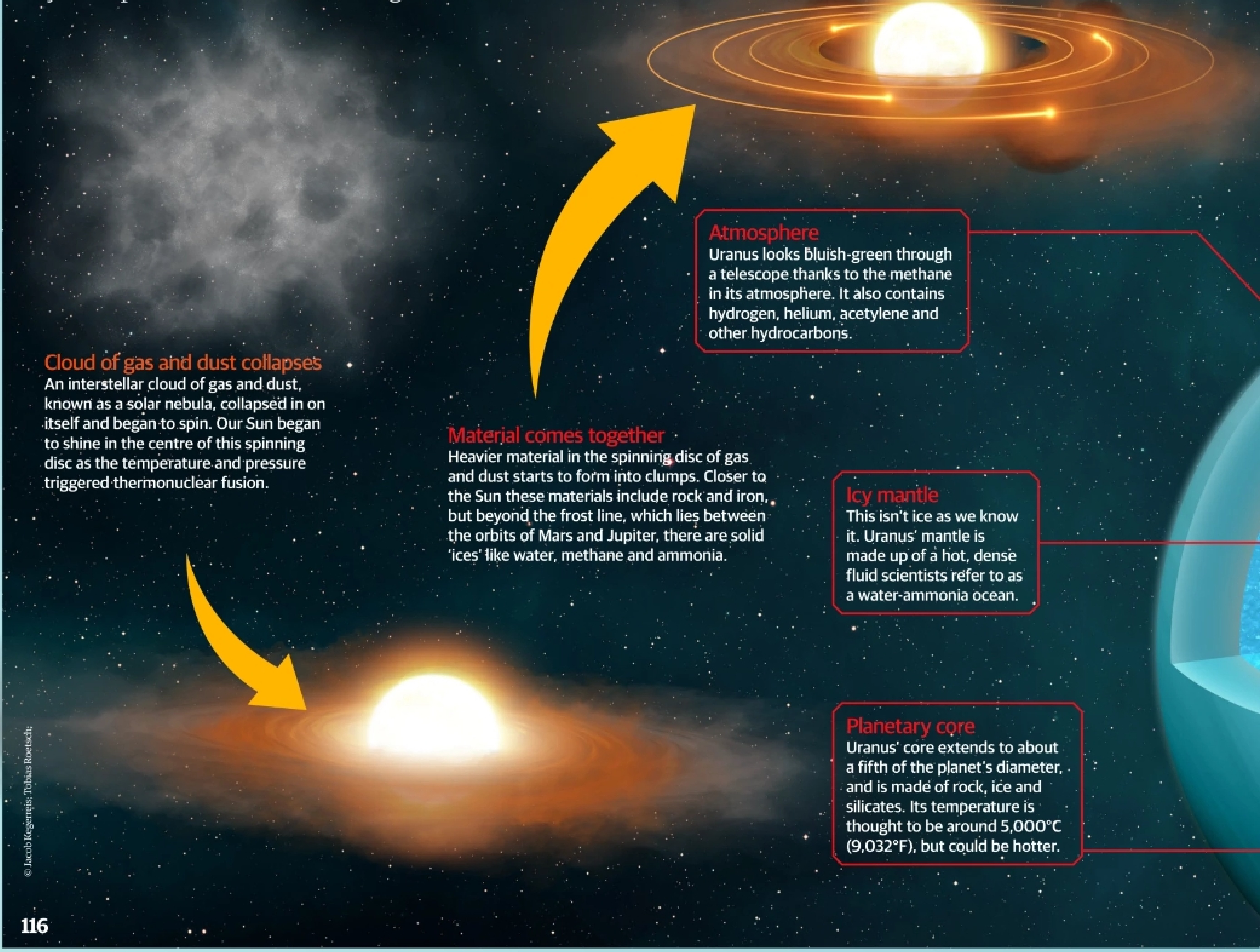
Voyager 2 sent back thousands of images and plenty of scientific data from Uranus. The spacecraft pinned down the length of time the planet takes to rotate as 17 hours, 14 minutes. It revealed the spectacular detail of the previously known rings around the planet, and discovered two new ones. As well as this the spacecraft spotted 11 previously unknown moons orbiting the planet and found evidence of geological activity on the five largest: Miranda, Ariel, Umbriel, Oberon and Titania.

Perhaps the strangest thing Voyager 2 discovered about Uranus was its strangely wonky magnetic field, tilted not at the same angle as the planet but instead at 59 degrees, and not appearing to originate from the planet's centre. This means the strength of the magnetic field in each hemisphere of the planet is different – compare that to the magnetic field strength on Earth, which is strongest at the north and south poles and weakest at the equator, and you start to understand how peculiar it is. Another as yet unexplained mystery of the planet is how cold it is. The lowest temperature recorded

> "Hubble revealed that Uranus has an active weather system with strong winds, bright clouds and even aurorae"

How an ice giant is made

Uranus formed in a similar way to the other Solar System planets before something hit it



Cloud of gas and dust collapses
An interstellar cloud of gas and dust, known as a solar nebula, collapsed in on itself and began to spin. Our Sun began to shine in the centre of this spinning disc as the temperature and pressure triggered thermonuclear fusion.

Material comes together
Heavier material in the spinning disc of gas and dust starts to form into clumps. Closer to the Sun these materials include rock and iron, but beyond the frost line, which lies between the orbits of Mars and Jupiter, there are solid 'ices' like water, methane and ammonia.

Atmosphere
Uranus looks bluish-green through a telescope thanks to the methane in its atmosphere. It also contains hydrogen, helium, acetylene and other hydrocarbons.

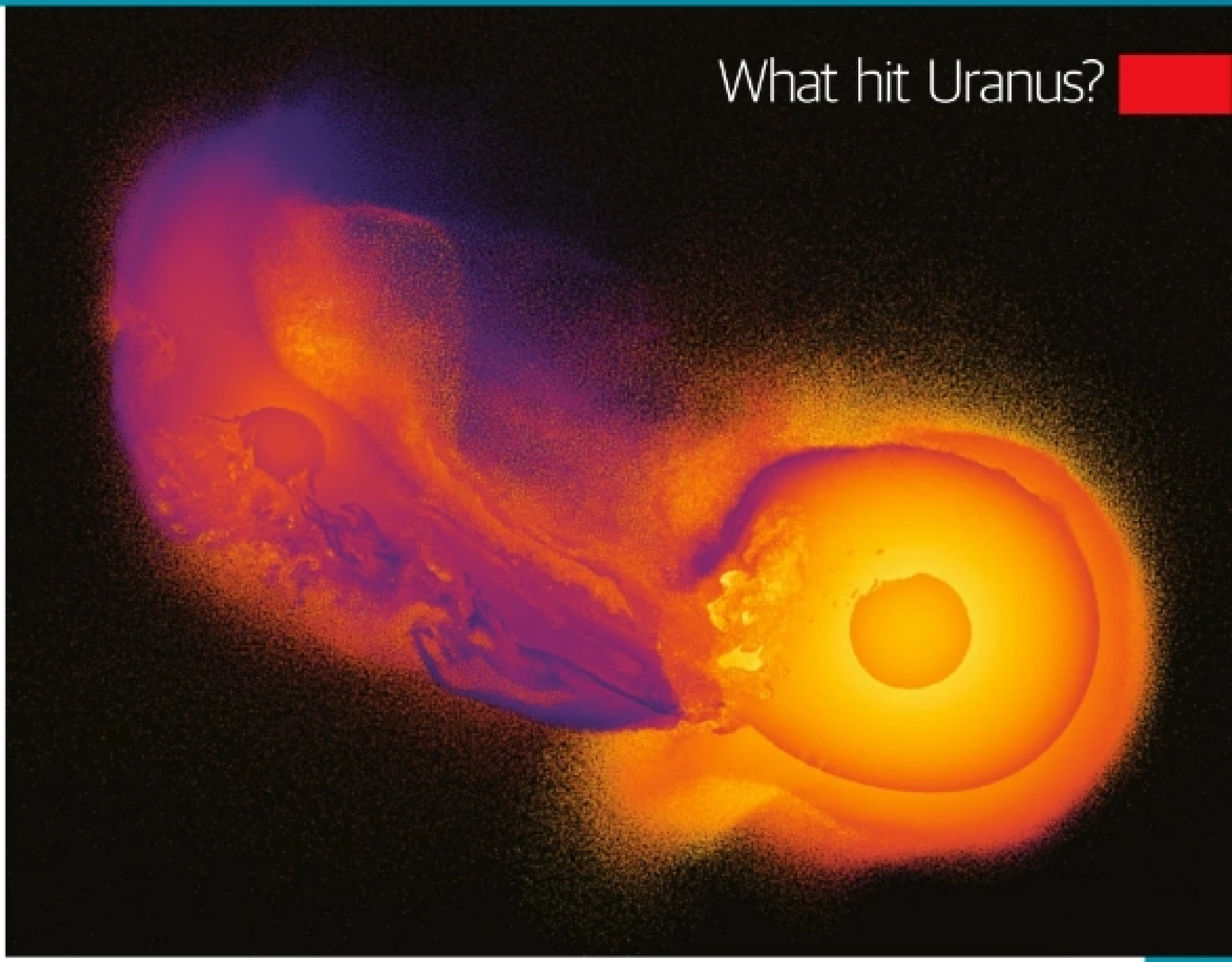
Icy mantle
This isn't ice as we know it. Uranus' mantle is made up of a hot, dense fluid scientists refer to as a water-ammonia ocean.

Planetary core
Uranus' core extends to about a fifth of the planet's diameter, and is made of rock, ice and silicates. Its temperature is thought to be around 5,000°C (9,032°F), but could be hotter.

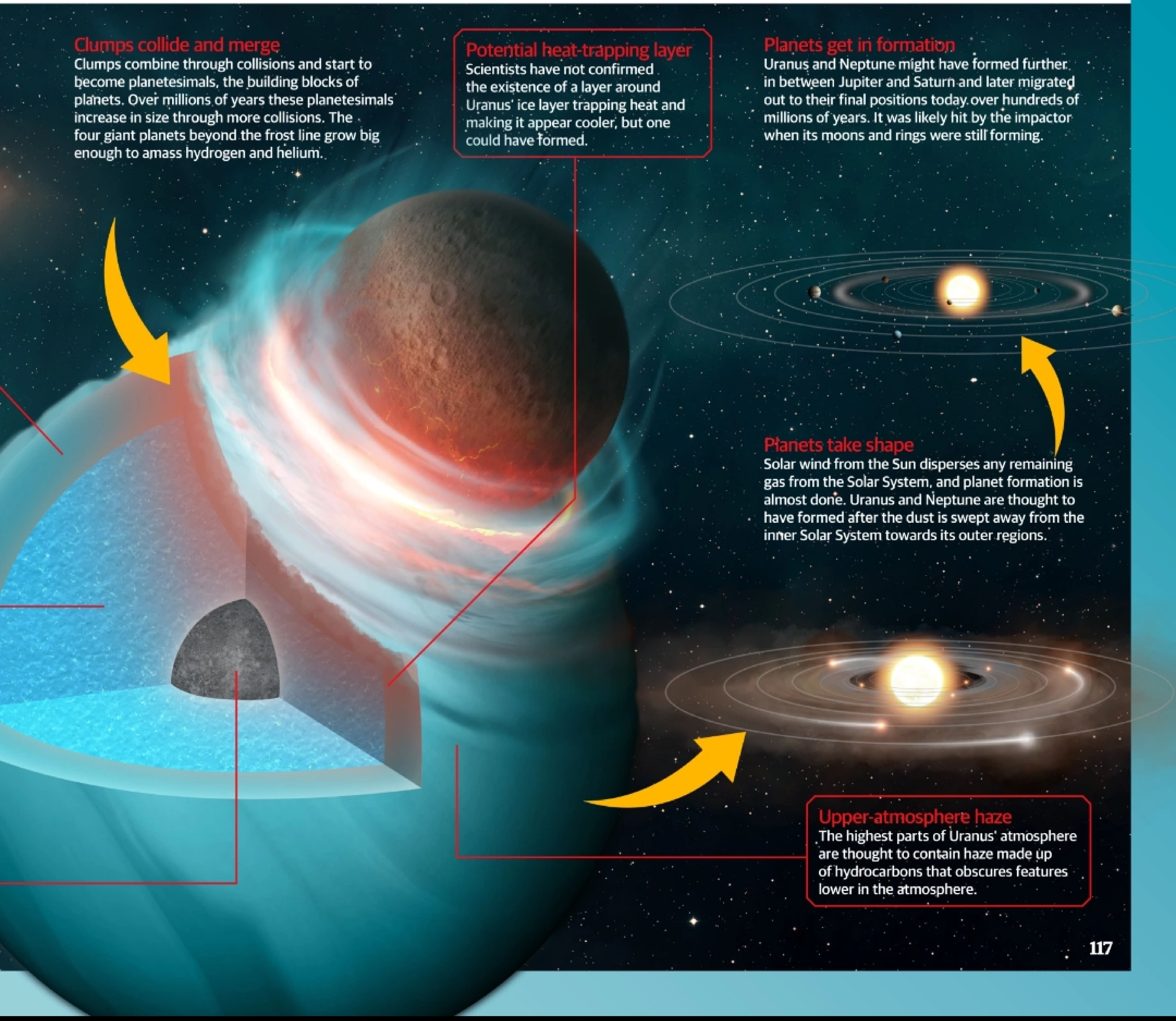
© Jacob Kegerreis; Tobias Roetsch;

on Uranus is −224.2 degrees Celsius (-371.56 degrees Fahrenheit). Other planets in our Solar System radiate more heat from their centres than they get from the Sun, but Uranus barely gives out any.

The answer to both of these mysteries might lie in what happened when Uranus became tilted. Planets are born out of discs of debris that circle nascent stars. When Uranus was formed it was likely spinning not too far off centre in much the same way as other planets in the Solar System. But new star systems in the process of forming are violent, hectic places. As well as the bodies that we know as planets today, there would have been potentially tens or hundreds of protoplanets - planets in a very early stage of formation, typically made of ice and rock - flying around the early Solar System. Once the initial debris disc around the Sun had disappeared, blown away by solar wind or cobbled together into other planets, these



Right: High-resolution simulations of a giant impact on Uranus, tilting the planet to the angle we see today



Clumps collide and merge
Clumps combine through collisions and start to become planetesimals, the building blocks of planets. Over millions of years these planetesimals increase in size through more collisions. The four giant planets beyond the frost line grow big enough to amass hydrogen and helium.

Potential heat-trapping layer
Scientists have not confirmed the existence of a layer around Uranus' ice layer trapping heat and making it appear cooler, but one could have formed.

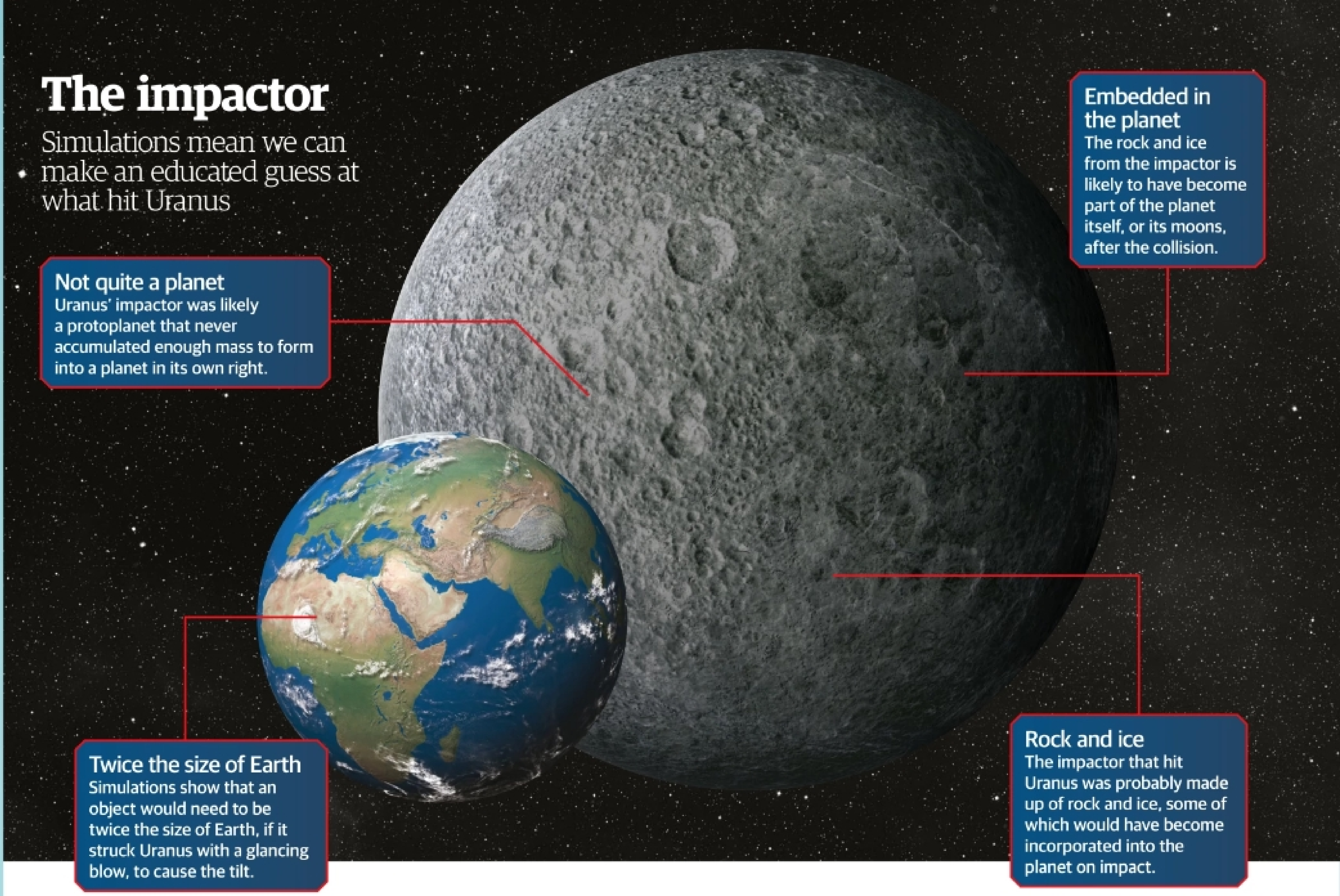
Planets get in formation
Uranus and Neptune might have formed further in between Jupiter and Saturn and later migrated out to their final positions today over hundreds of millions of years. It was likely hit by the impactor when its moons and rings were still forming.

Planets take shape
Solar wind from the Sun disperses any remaining gas from the Solar System, and planet formation is almost done. Uranus and Neptune are thought to have formed after the dust is swept away from the inner Solar System towards its outer regions.

Upper-atmosphere haze
The highest parts of Uranus' atmosphere are thought to contain haze made up of hydrocarbons that obscures features lower in the atmosphere.

The impactor

Simulations mean we can make an educated guess at what hit Uranus



Not quite a planet
Uranus' impactor was likely a protoplanet that never accumulated enough mass to form into a planet in its own right.

Embedded in the planet
The rock and ice from the impactor is likely to have become part of the planet itself, or its moons, after the collision.

Twice the size of Earth
Simulations show that an object would need to be twice the size of Earth, if it struck Uranus with a glancing blow, to cause the tilt.

Rock and ice
The impactor that hit Uranus was probably made up of rock and ice, some of which would have become incorporated into the planet on impact.

protoplanets would have become less stable and potentially ended up on collision paths with their fully grown siblings.

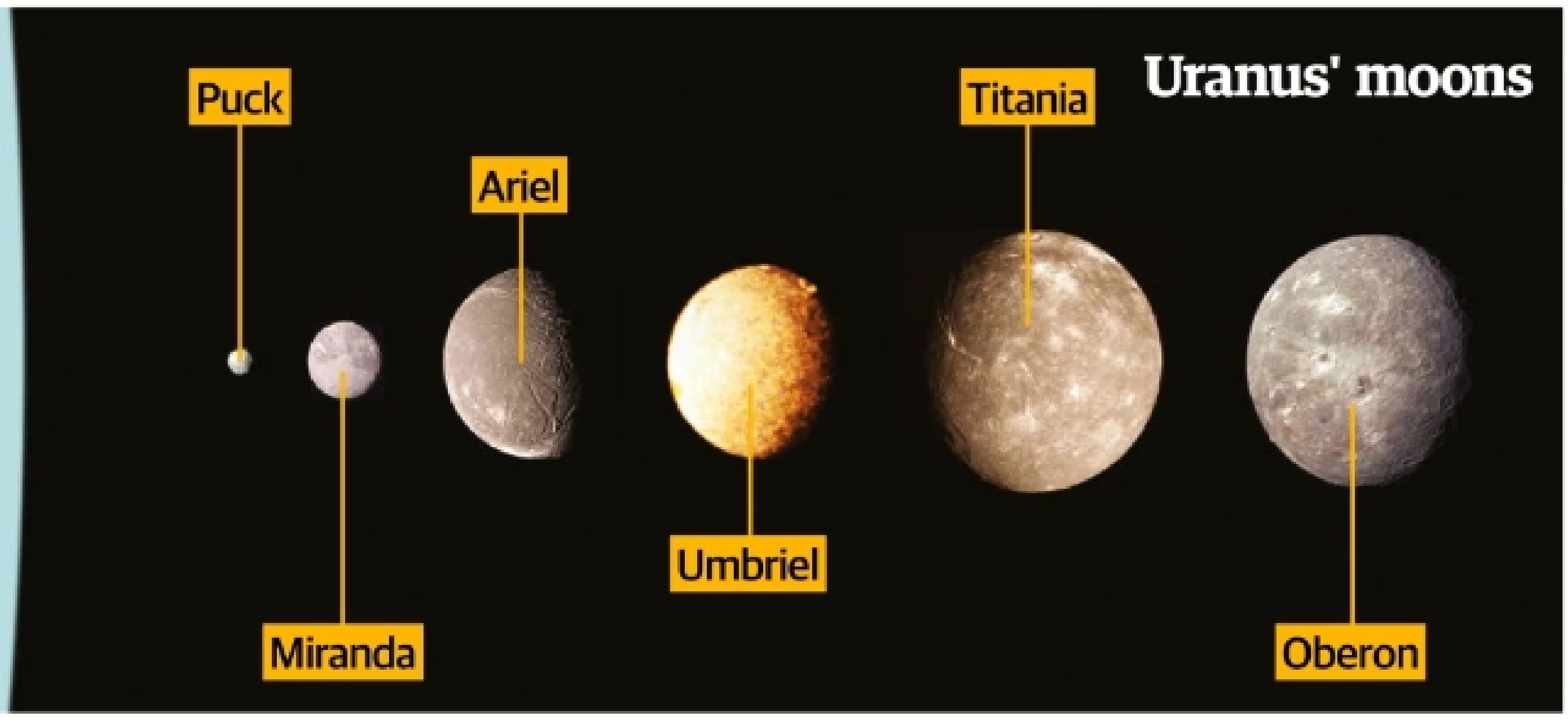
A protoplanetary hit job is the leading theory. "The giant-impact scenario is still the leading hypothesis to explain the high obliquity of Uranus," says Nadine Nettelman, a planetary scientist at the University of Rostock in Germany. Scientists think that as well as being responsible for the tilt of Uranus, giant impacts are to blame for other Solar System phenomena, including Earth's own Moon and Saturn's rings.

The trouble is we've never seen one of these impacts first hand, and we can't invent a time machine to go back to the early Solar System to check the hypothesis. Instead, researchers are using supercomputers to simulate these sorts of collisions and get to the bottom of what might have happened to Uranus. "We have millions of particles that we put down in our computer and we tell the computer simulation how those particles behave," says Kegerreis, who is part of a project using the technique, called smoothed-particle hydrodynamics, to investigate the giant planet. The researchers input information about how gravity works, what pressure the materials would be under, their density and temperature. "And then we just let those particles smash into each other and evolve the physics as the simulation does," says Kegerreis, "and see where they go."

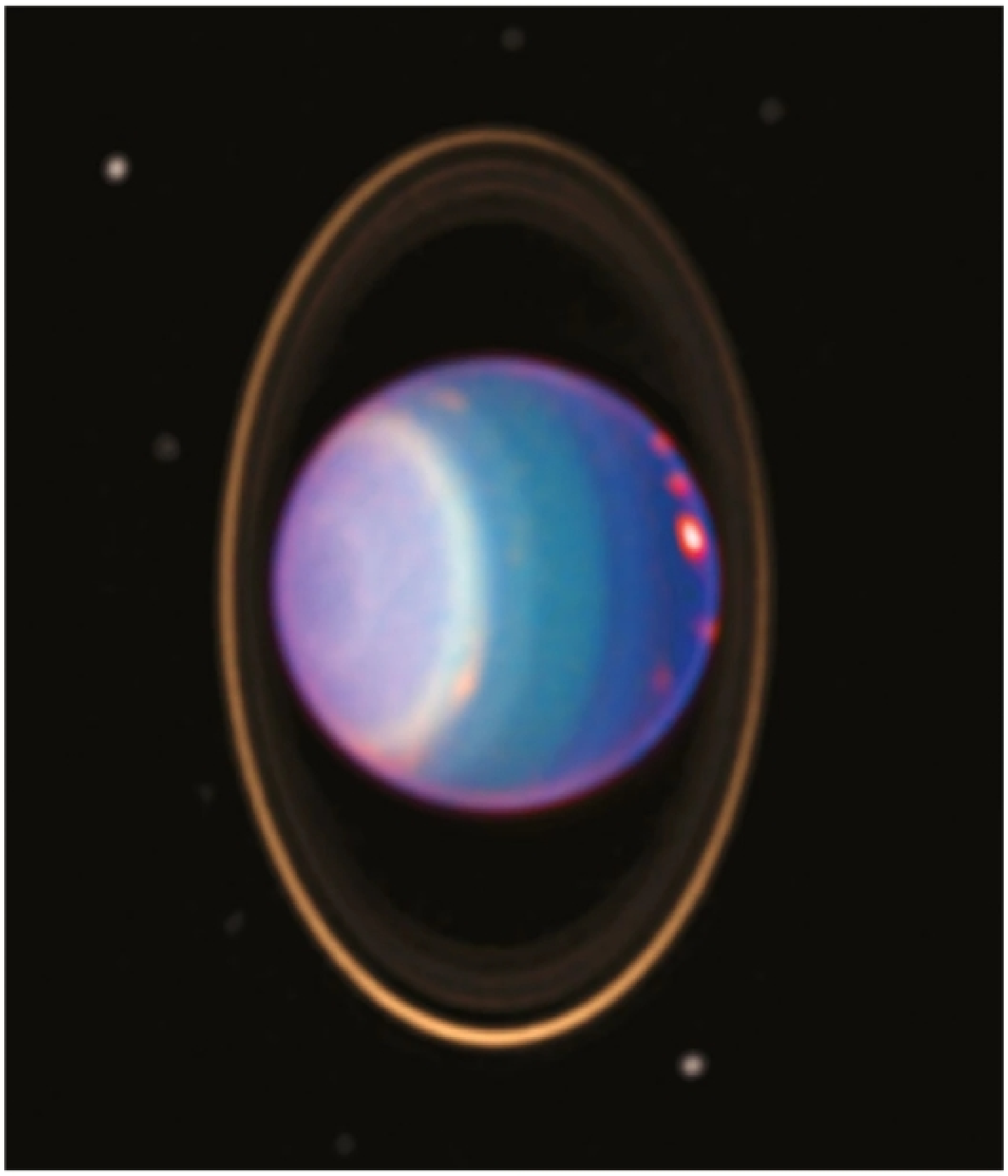
The latest simulations, presented in a talk at the American Geophysical Union's annual conference last year, show that the impactor could have been an object twice the size of Earth. The object – likely a protoplanet left over from the formation of the Solar System – striking a grazing blow on Uranus would have been enough to knock it off-kilter, but not so violent as to make it lose the atmosphere that we still see surrounding the planet today.

Another finding from the simulations might explain why Uranus is so cold all of the time: debris from the impactor could have made a thin shell around the planet's ice layer, sealing in the inner heat. Nettelman, who published a paper suggesting the existence of such a 'thermal boundary layer' in 2016, says that this layer "prevents heat flow from escaping the deep interior". But it's too early on to rule out all other options when it comes to what hit Uranus; there's a chance the impactor could have been a smaller object in certain circumstances, for instance. If the planet was already tilted by the time an Earth-sized protoplanet hit it, this could have been enough of an extra push to give it the extreme tilt we see today.

The mass could have been bigger as well. "That would obviously be able to knock it over just as easily," says Kegerreis. "But the bigger you make the impact, the less likely it is for that to exist in terms of what would have been flying around the early



Uranus' moons



> "The bigger you make the impact, the less likely it is for that to exist in terms of what would have been flying around" **Jacob Kegerreis**

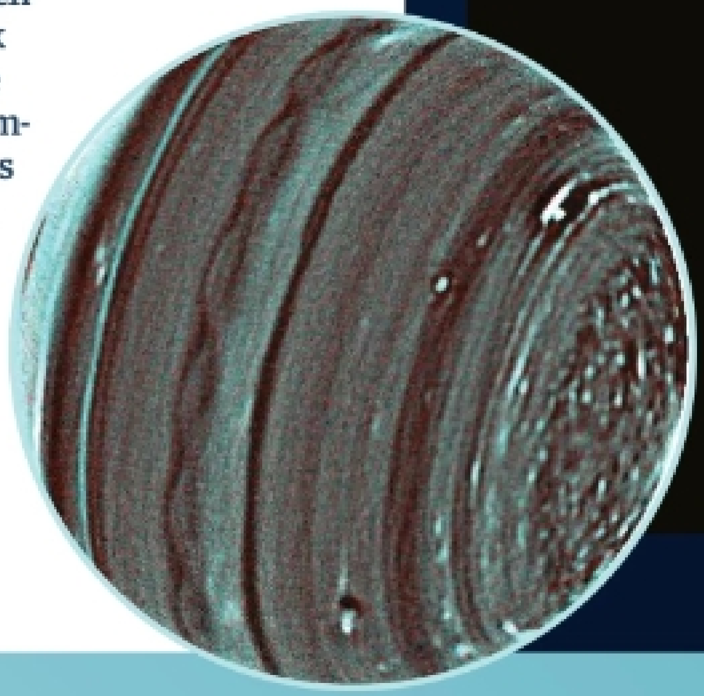
Solar System." There may be remnants of whatever hit Uranus embedded within the planet itself. In the simulations the researchers saw that an impactor could have left lumps of rock inside the planet. These might even be what's causing the ice giant's magnetic field to be tilted strangely and off-centre.

The moons could also provide clues about the impactor. The fact that the major moons of Uranus orbit around the planet's equator suggest that they were either formed from the debris left over after the impact or, if they were already in the process of forming when Uranus was hit, were dragged over when the planet was destabilised.

For his part, Kegerreis says the team is spoilt for choice about what to use the simulations to investigate next. They may look in more detail into what could have caused Uranus' lumpy, lopsided magnetic field, or probe how giant impacts can mix up and change the atmosphere of ice giant planets in general. "We've only just scratched the surface of what we can do with these big simulations," he says.

Above: This false-colour image by Hubble shows bright clouds in the planet's atmosphere in orange

Below: An infrared image of Uranus taken by the Keck II telescope shows storm-like features and clouds



Hubble watches the ice giant's weather

Words by **Meghan Bartels**

In cooperation with SPACE.com

If you don't like your local weather, perhaps you would prefer the atmosphere on Uranus or Neptune – and the Hubble Space Telescope has an update on each planet's current conditions.

The telescope regularly checks in on the two outer planets to see what's happening in their atmospheres, and last autumn Hubble captured incredible images of clouds on both worlds.

Uranus is currently deep into its summer season, and that shows in the giant, white cloud covering the planet's north pole, which currently points towards the Sun. As scientists have watched the Uranian summer progress – a season on this distant, giant world lasts 21 Earth years – they have seen this massive cloud grow even bigger. The large polar cap is accompanied by a smaller, bright cloud of methane ice.

On Neptune, where seasons last for 41 Earth years, it's winter in the northern hemisphere. That hemisphere is currently sporting a massive dark storm that stretches about 11,000 kilometres (6,800 miles) across.

Scientists aren't sure what phenomenon creates Neptune's dark storms, although the tempests seem to pop up about twice a decade and disperses within about two years. Researchers suspect that the storms creep upwards through the planet's atmosphere, lifting the ingredients of deeper layers of the atmosphere to the top.

Near the dark storm currently on Neptune, Hubble spotted another atmospheric feature: sparkling white 'companion clouds', which scientists have spotted around dark storms in the past. Astronomers suspect that these bright clouds are full of methane ice that's been rapidly pushed upwards and frozen.

Below: Uranus and Neptune as observed through Hubble

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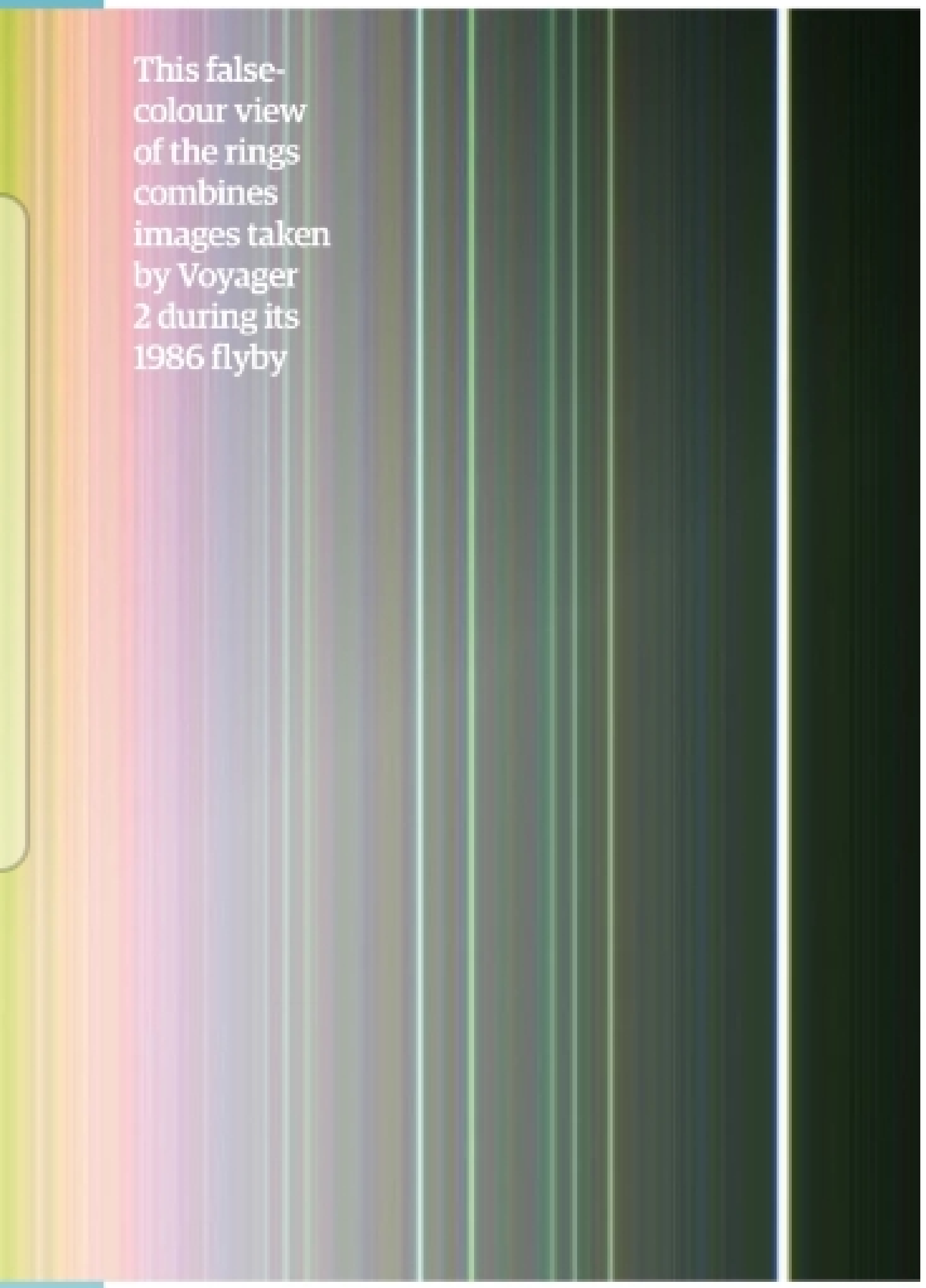


This false-colour view of the rings combines images taken by Voyager 2 during its 1986 flyby

> "We really need to figure out if our understanding of Uranus would benefit from a dedicated mission" **Nadine Nettelman**

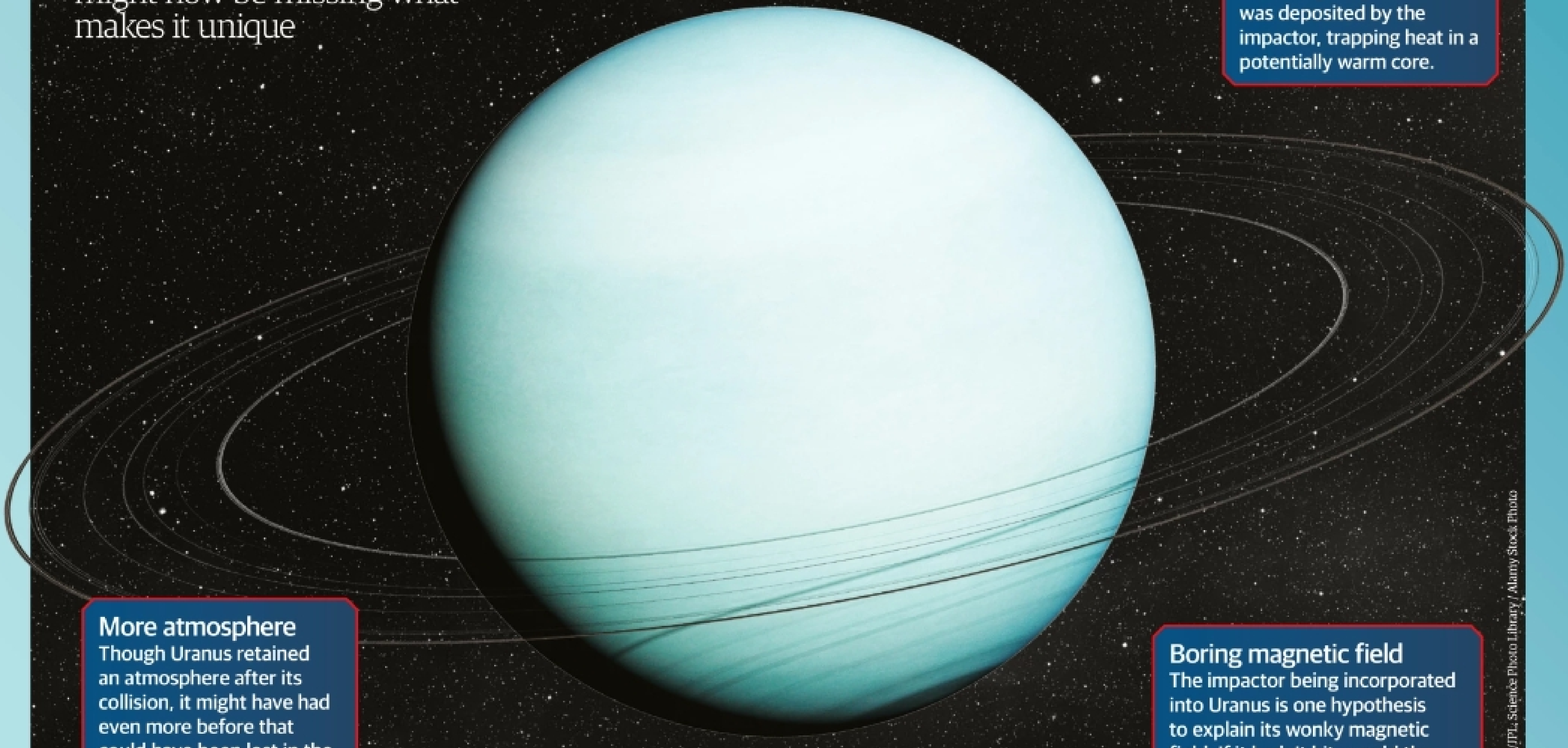
Despite the progress made in recent years, there are still many things left unexplained about Uranus. We still don't know how hot or cold the core of the planet is because we haven't pinned down the details of the possible thermal boundary layer that could be trapping in the heat. We know that Uranus and Neptune have similar magnetic fields, but we don't know why they have such different heat flows. Its icy sibling Neptune is also largely a mystery, having similarly only been visited by the Voyager 2 spacecraft in the summer of 1989. "Compared with pretty much all the other planets, apart from Neptune which is in the same position, an awful lot of the details we really don't know very well," confirms Kegerreis.

Thrusting Uranus and Neptune into the spotlight recently is the fact that a lot of the exoplanets astronomers have been finding outside of the Solar System are similar, at least in size, to the ice giants. In 2014 when Kepler announced the discovery of an incredible 715 new worlds in one go, roughly half of them were similar in size to Neptune. Learning more about the giant planets on our doorstep will make figuring out the details of faraway alien planets much easier.

Some researchers think the only way to really get to grips with Uranus will be a dedicated mission, and in recent years there have been several proposed missions to the ice giant. "I think the time is right, but the planning should not be hasted," says Nettelman. "We really need to figure out if our understanding of Uranus would benefit from a dedicated mission, or maybe more from a combined mission to both Uranus and Neptune." Combining theory and simulations with actual observations will help us get to the bottom of the mysteries hiding underneath Uranus' deceivingly calm exterior. Maybe it'll even teach us something about the whole universe of planets outside our Solar System, too.

What if Uranus hadn't been tipped over?

If it hadn't been hit, the planet might now be missing what makes it unique



Upright tilt
Astronomers expect Uranus started off with a much more slight tilt, if it had one at all. If it hadn't been hit it would have stayed that way.

A warmer exterior
The ice giant's cool appearance could be caused by a layer that was deposited by the impactor, trapping heat in a potentially warm core.

More atmosphere
Though Uranus retained an atmosphere after its collision, it might have had even more before that could have been lost in the violent impact.

Boring magnetic field
The impactor being incorporated into Uranus is one hypothesis to explain its wonky magnetic field. If it hadn't hit, would the magnetic field be less strange?

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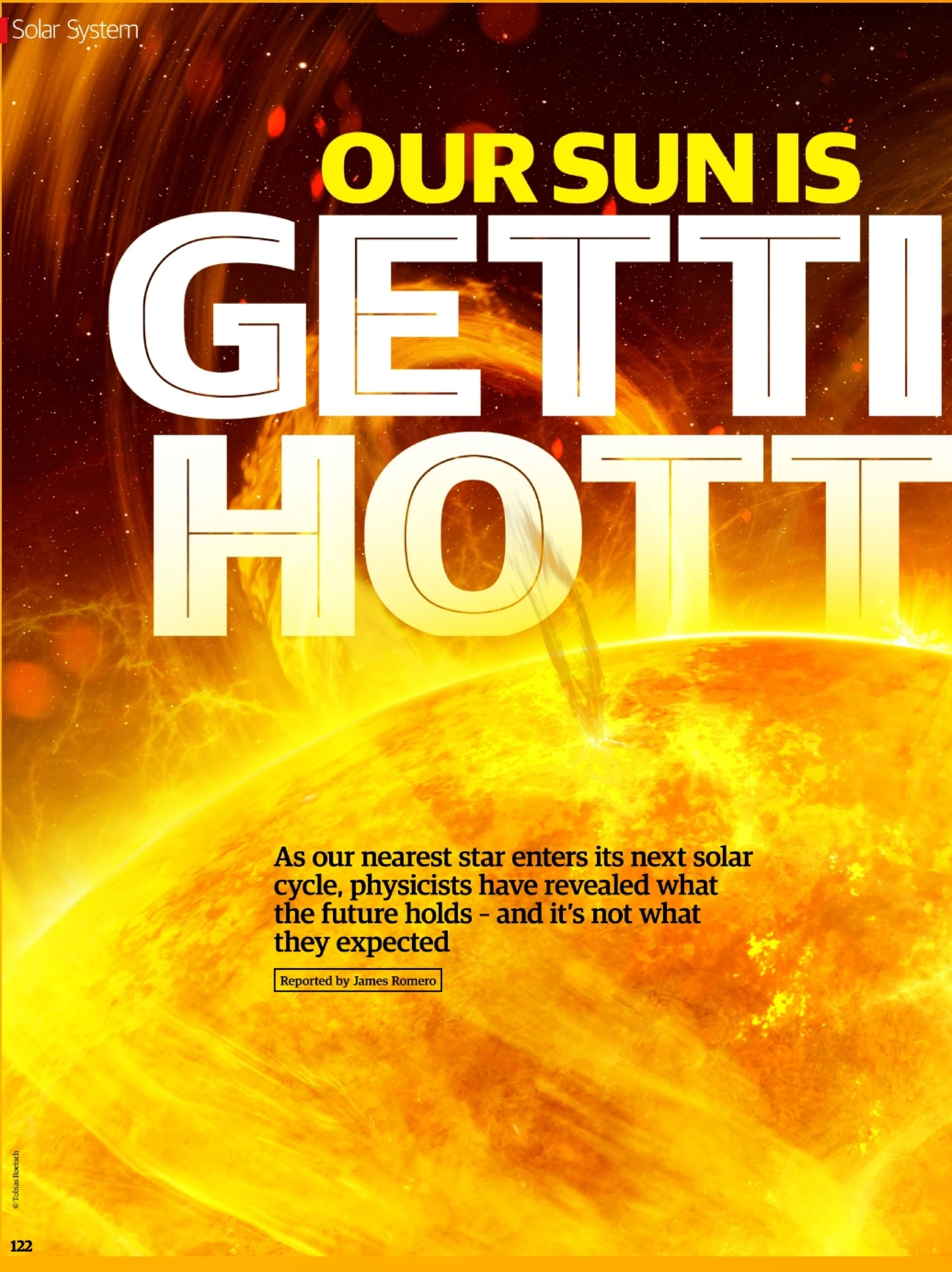


OUR SUN IS GETTI HOTT

As our nearest star enters its next solar cycle, physicists have revealed what the future holds - and it's not what they expected

Reported by James Romero

© Tobias Roetsch

As a life-giver that warms and lights up our world, it is easy to forget the true, violent nature of the Sun. As the Sun enters a new cycle of surface activity, we are only now beginning to fully appreciate the wide-ranging ways our star's changeable nature can impact our planet and modern lives.

Solar weather describes the influence of the Sun on the Earth-space environment. Back in 2011 it was added to the UK government's National Risk Register and placed on a similar level to the emergence of a new disease due to the number of people it could potentially impact on Earth.

"The Sun is very dynamic," says Helen O'Brien, lead engineer on the European Space Agency's Solar Orbiter mission. "It has different moods, it is very explosive and it has the potential to damage our modern infrastructure." As well as providing heat and light, our star is constantly throwing out more deadly material. The solar wind is the name given to this constant stream of energised, charged particles, primarily electrons and protons.

On Earth we are shielded by our planet's magnetic field while high-energy X-rays and ultraviolet light are absorbed high up in the atmosphere. They electrify their surroundings to create the Earth's ionosphere and simultaneously excite constituents of our own atmosphere so they glow and create the famous aurorae.

While the aurorae are harmlessly enjoyed by polar communities and tourists, the Sun's own magnetic field can throw far more violent eruptions our way. Its much larger field is composed of a series of magnetic lines that connect distant points on the surface. Over time these lines can become twisted as the Sun's compositional fluidity sees material at its equator rotate faster than at its poles, and the magnetic field gets wrapped around the star. "When you distort a magnetic field it is like stretching an elastic band," says Chris Scott, professor of Space and Atmospheric Physics at the University of Reading. "You are storing up energy."

> "[The Sun] is very explosive and has the potential to damage our modern infrastructure"
>
> **Helen O'Brien**

Those magnetic distortions cause complex knots to form, which burst to the surface as sunspots. When the Sun is very active you have lots of energy stored up in these knots, and occasionally the system will reconfigure itself through solar flares that throw out vast quantities of high-energy plasma like a cloud from the Sun's atmosphere.

These eruptions can be incredibly violent. The largest, known as coronal mass ejections, can contain billions of tonnes of material, which travels out at speeds of several million miles per hour.

NASA's Solar Dynamics Observatory captured this image of a solar flare on 2 October 2014

If Earth is in the crosshair of these large storms the consequences can be both spectacular and costly. This was evident even back in September 1859 on the night of the most famous direct hit, known as the Carrington event, which bathed almost the entire surface of the Earth in beautiful aurorae. Though Carrington was spectacular in its scale and spectacle, it was also the first example of solar weather impacting our technology - recently rolled out telegraph systems in America and Europe were hit by fires and gave people electric shocks.

In today's information age of integrated power networks and satellite communications, a similar strike today could bring down radio communications and upset electronics on the ground, causing long-distance power grids to fail. In 1989 a coronal mass ejection blacked out the entire Canadian province of Quebec, while last year an economic risk assessment by researchers from the University of Oxford found that a Carrington-style event could leave the UK with £15.9 billion (approximately $20.5 billion) worth of damage.

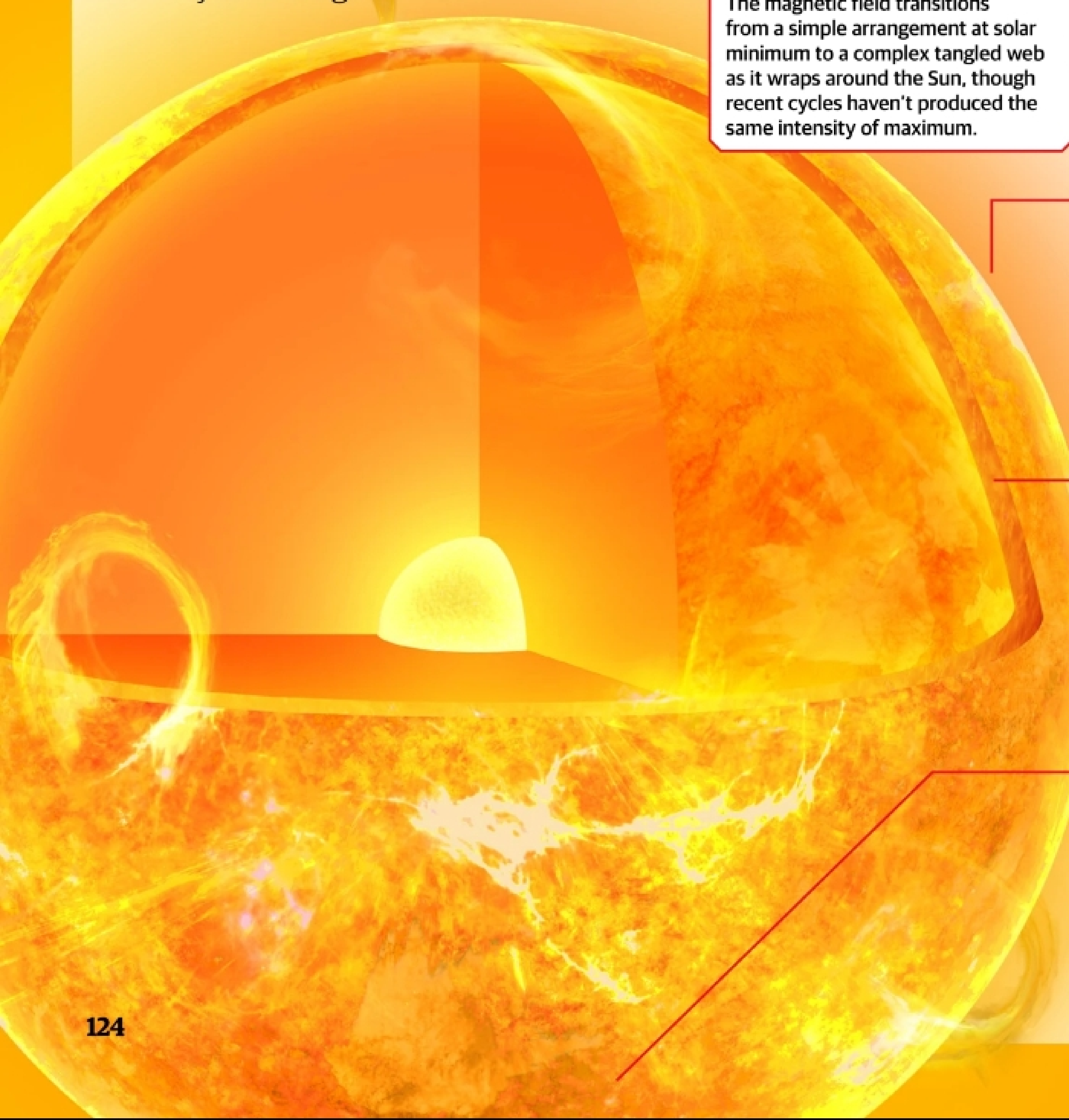
In general, a direct threat to human life on the Earth's surface is low. However, a small proportion of our population are spending more and more time higher up, and that does create risks. Storms increase the radiation impacting spacecraft to levels that could threaten astronaut health, while more transatlantic flights are crossing the poles where solar wind material is constantly funnelled by Earth's magnetic field.

Exposure from a single flight during normal solar conditions will be tiny, but there is concern for flight staff working up there year round. Also, recent research from Clive Dyer of the University of Surrey Space Centre suggests flying in modern aircraft

> "A strike today could bring down radio communications and upset electronics on the ground, causing power grids to fail"

What's going to happen to the Sun?

Each layer of our home star is affected in the cycle change



Sun's magnetic field

The magnetic field transitions from a simple arrangement at solar minimum to a complex tangled web as it wraps around the Sun, though recent cycles haven't produced the same intensity of maximum.

Corona

Though generally marked by lower output, solar minimums can still see heightened periods of high-energy particles released from this upper-atmospheric layer as the Sun's magnetic field creates holes in the corona. However, it's during the solar maximum when the corona will be most active, full of spinning tornados, nanoflares and looped-shaped helmet streamers. As you move towards solar maximum solar flares push more frequently through the corona, heating its gas up.

Photosphere

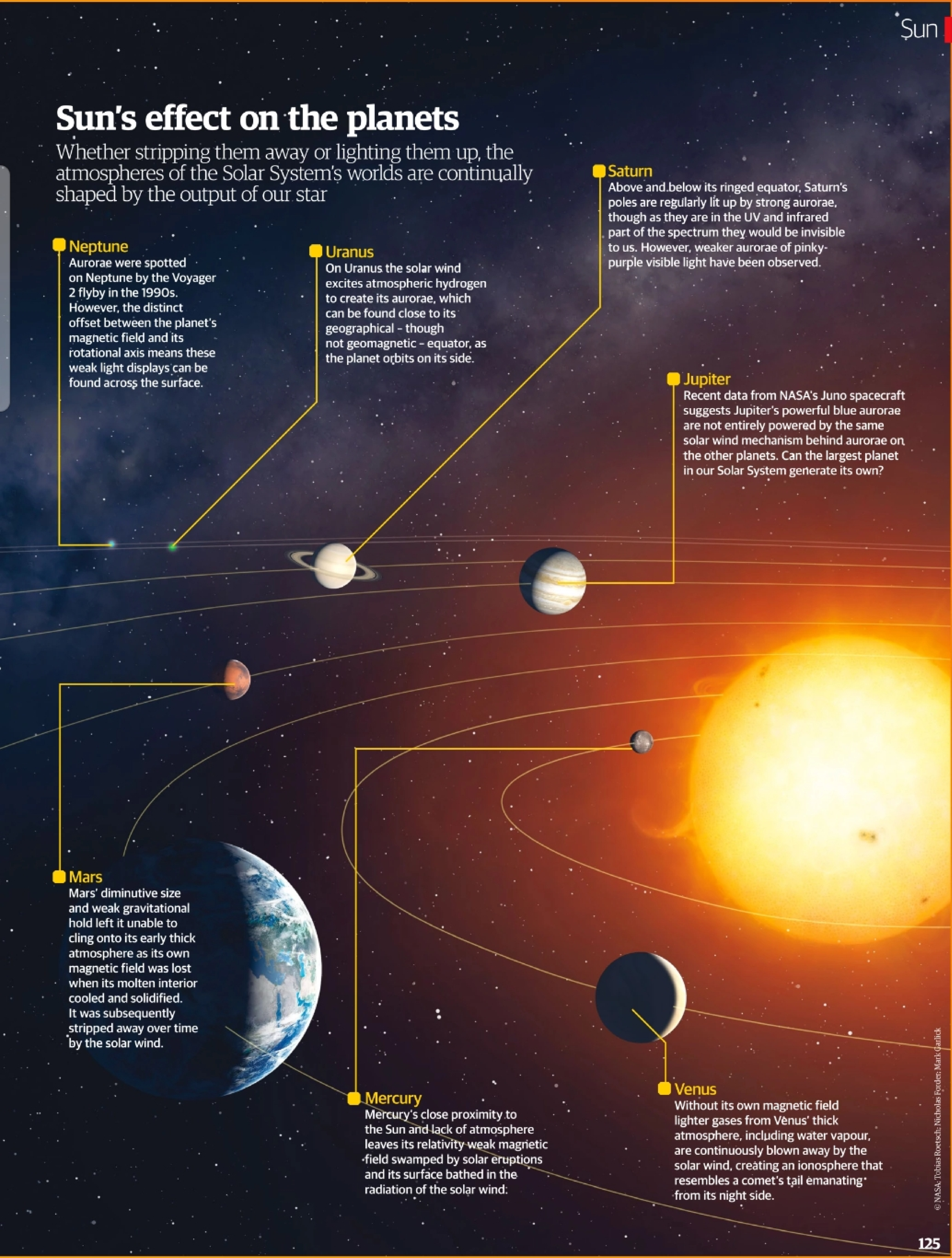
On the surface of the lowest layer of the Sun's atmosphere, the start of a new cycle is marked by the appearance of sunspots in higher latitudes. Solar flares also become much more common as you approach solar maximum.

Chromosphere

The second of the Sun's three atmospheric layers experiences frequent heating by ascending solar flares as you approach the solar maximum. Solar prominences, gigantic plumes of gas rising up from the photosphere, are also more abundant at solar maximum and during louder solar cycles. As are spicules, jet eruptions of gas that shoot upwards and outwards into the corona.

Sun's effect on the planets

Whether stripping them away or lighting them up, the atmospheres of the Solar System's worlds are continually shaped by the output of our star



Neptune
Aurorae were spotted on Neptune by the Voyager 2 flyby in the 1990s. However, the distinct offset between the planet's magnetic field and its rotational axis means these weak light displays can be found across the surface.

Uranus
On Uranus the solar wind excites atmospheric hydrogen to create its aurorae, which can be found close to its geographical – though not geomagnetic – equator, as the planet orbits on its side.

Saturn
Above and below its ringed equator, Saturn's poles are regularly lit up by strong aurorae, though as they are in the UV and infrared part of the spectrum they would be invisible to us. However, weaker aurorae of pinky-purple visible light have been observed.

Jupiter
Recent data from NASA's Juno spacecraft suggests Jupiter's powerful blue aurorae are not entirely powered by the same solar wind mechanism behind aurorae on the other planets. Can the largest planet in our Solar System generate its own?

Mars
Mars' diminutive size and weak gravitational hold left it unable to cling onto its early thick atmosphere as its own magnetic field was lost when its molten interior cooled and solidified. It was subsequently stripped away over time by the solar wind.

Mercury
Mercury's close proximity to the Sun and lack of atmosphere leaves its relativity weak magnetic field swamped by solar eruptions and its surface bathed in the radiation of the solar wind.

Venus
Without its own magnetic field lighter gases from Venus' thick atmosphere, including water vapour, are continuously blown away by the solar wind, creating an ionosphere that resembles a comet's tail emanating from its night side.

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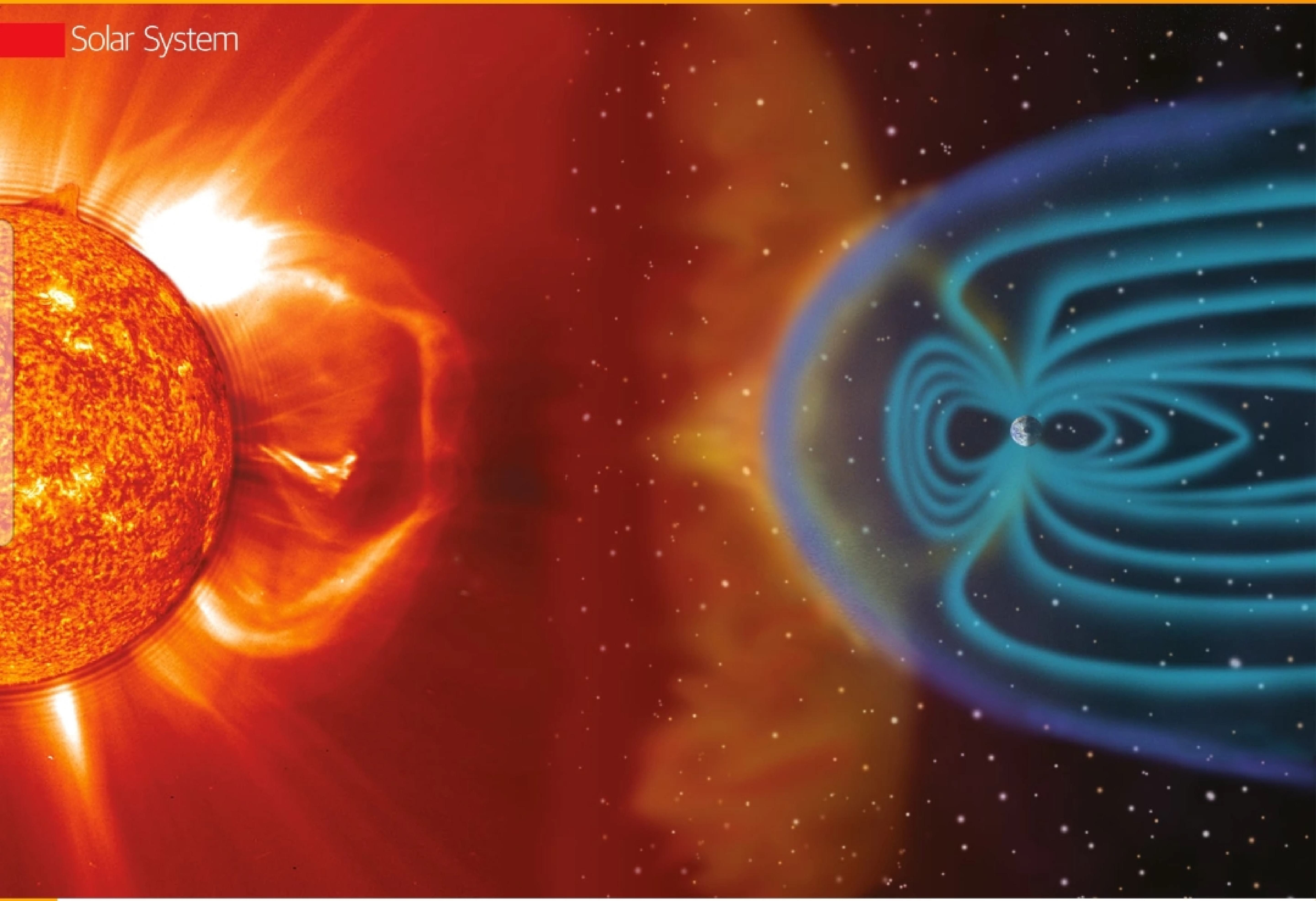
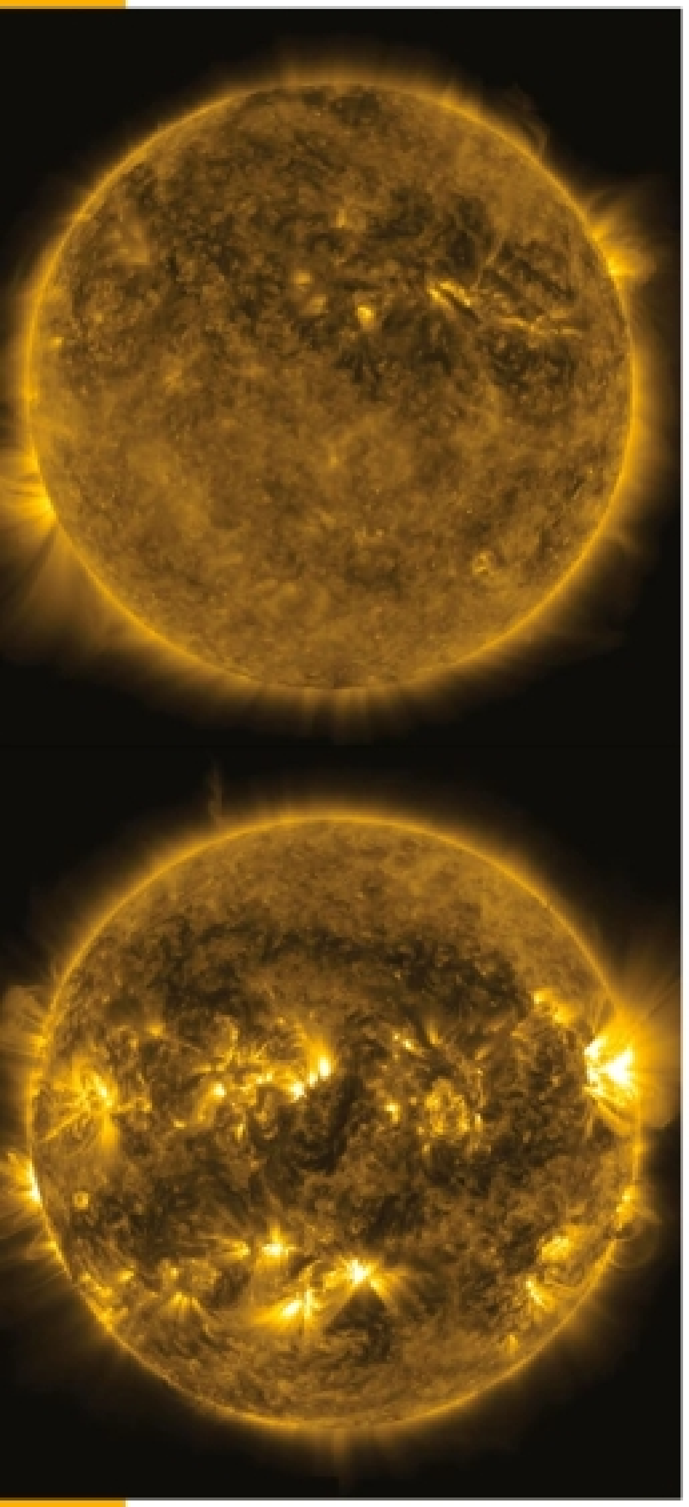




during a solar storm could expose passengers to radiation levels equivalent to the annual working limit for air crews. This threat has left satellite companies, aircraft operators and power companies monitoring the solar cycle for clues as to when the threat level will be at its highest.

By counting sunspots on the Sun's surface scientists have for some time known of 11-year cycles of increasing and decreasing solar activity and surface eruptions, driven by the tangling and untangling of the magnetic field lines. These plots indicate we are approaching the latest solar minimum, and therefore entering a new cycle.

Recent magnetic field evolution models developed by the Center of Excellence in Space Sciences in India concluded that the solar maximum of the next cycle, solar cycle 25, will occur around 2024. They also suggested the cycle could buck a wider trend of decreasing solar maximum intensities since the early 1990s, though perhaps not in a way that would greatly threaten ground- or space-based infrastructure.

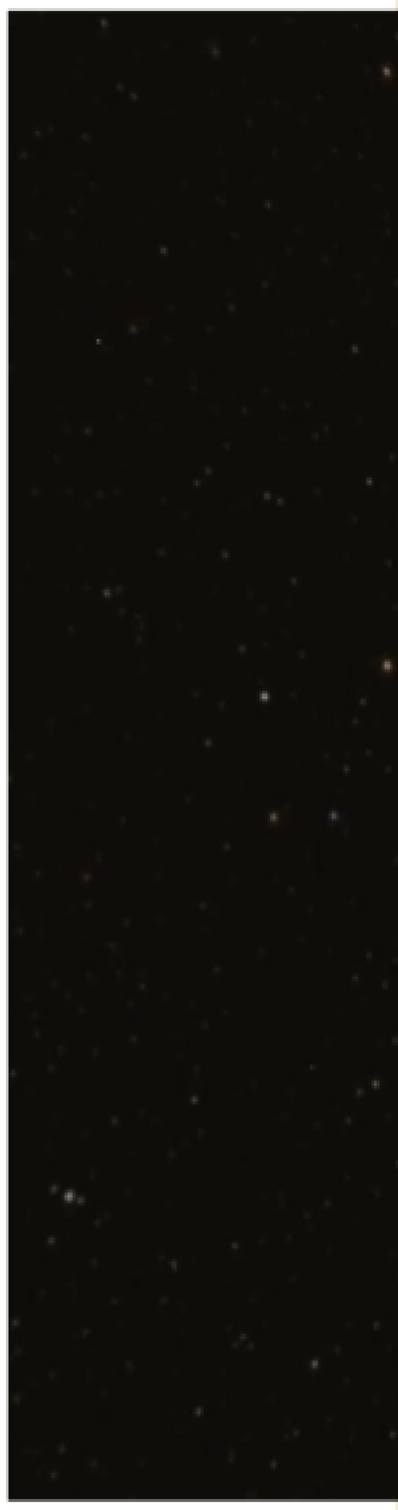
"It is unlikely that this will affect big solar storms, as these can happen at any stage of the solar cycle," says Scott. However, anticipating the timing and severity of the coming solar cycle could help us prepare for the more local effects such solar variability that effect our lives and which have only come to light in the last decade or two.

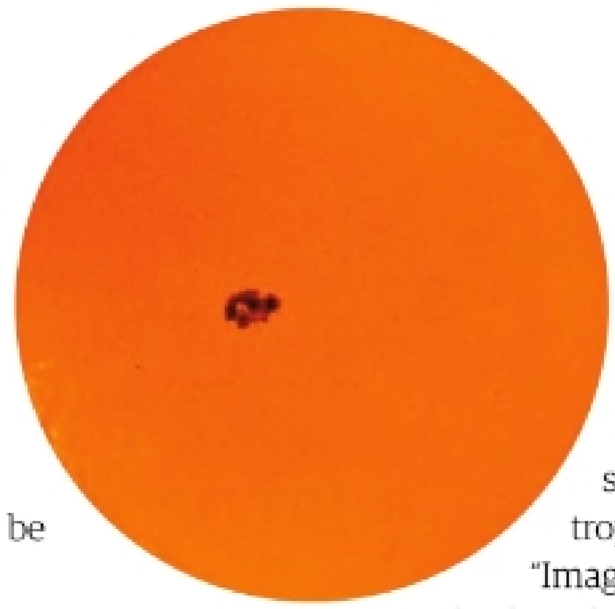
Researcher Pablo Mauas has published a series of papers analysing river flows of the Paraná River, as well as measuring snow accumulation and counting tree rings to establish a remarkable agreement between local precipitation rates and the number of sunspots, tracked back over many decades. "I can quite believe there is an 11-year cycle in the flow rates of the river," says Scott, who points to evidence of similar solar-influenced systems closer to home.

During recent low periods of solar activity it seems the jet streams become more meandering, and you get more 'blocking events' where air-pressure systems get stuck over a certain location. These phenomena are thought to account for some of the very cold recent winters in northwest Europe, but perhaps this trend may reverse slightly if the next solar cycle is more active, as the Indian research team suggests.

In his own research Scott has shown that fast jets of solar wind passing the Earth, associated with more active solar periods, can result in a substantial increase in lightning strikes across Europe for up to 40 days as a result of disturbances to the electrical properties of the atmosphere. While communities and populations may need to adapt to changes in these localised weather systems, a better way of predicting larger scale solar weather on a more detailed day-to-day basis is an urgent priority.

This becomes more pressing if Carrington events prove to be more common than that 'once-in-a-century' tag. Reanalysis of magnetic behaviour measurements in the Earth's atmosphere by Scott's colleague Mike Lockwood has found storms in





1941 and 1972 that may have been as big, if not bigger, than Carrington, but had surprisingly little impact. "It might be that the biggest parts occurred over parts of the world where there wasn't the technological infrastructure to be disturbed," says Scott.

There was also a storm in July 2012 that narrowly missed the Earth and fortunately hit a solar-observation spacecraft from the Solar TErrestrial RElations Observatory (STEREO) mission. It was travelling fast enough that if it had been on target it would have triggered a modern-day Carrington-like event. If we are not to be so fortunate during the next solar cycle we will need to investigate ways to provide more detailed forecasts of what is coming at us.

"It's like on Earth; we can say the winter will be colder than the summer and we will get more rain," says O'Brien. "But what you really want to know is if it is going to rain on the day of your party." However, there are challenges replicating our ability to predict Earth weather in space.

Meteorologists utilise a vast network of monitors collecting data 24/7 as satellites constantly track weather systems from above in order to run their increasingly sophisticated simulations.

And while we have models of the solar wind and how it propagates through space and interacts with the Earth, we can't look down on the entire system as we can when tracking tropical storms or rain fronts.

"Imagine yourself as a meteorologist back in the pre-space age in the 1950s, and you are trying to make sense of all these spot measurements without the benefits of a satellite picture. That's probably where we are with space weather," says Scott.

Reliable space weather forecasts will also require a greater understanding of the relationship between what we see on the Sun's surface and what is in line to hit us several hours or days later. To help in this endeavour we have sent up a community of craft to monitor the Sun. However, they are all primarily scientific missions sent up to answer scientific questions. "They are proving useful, but they are not optimal," says Scott, whose STEREO mission can only provide data at the end of each day, which isn't much use when really powerful, fast-moving storms can get to Earth in 17 hours.

The scientific community are in regular contact with industry and space agencies who are working to ensure they have spares at the most

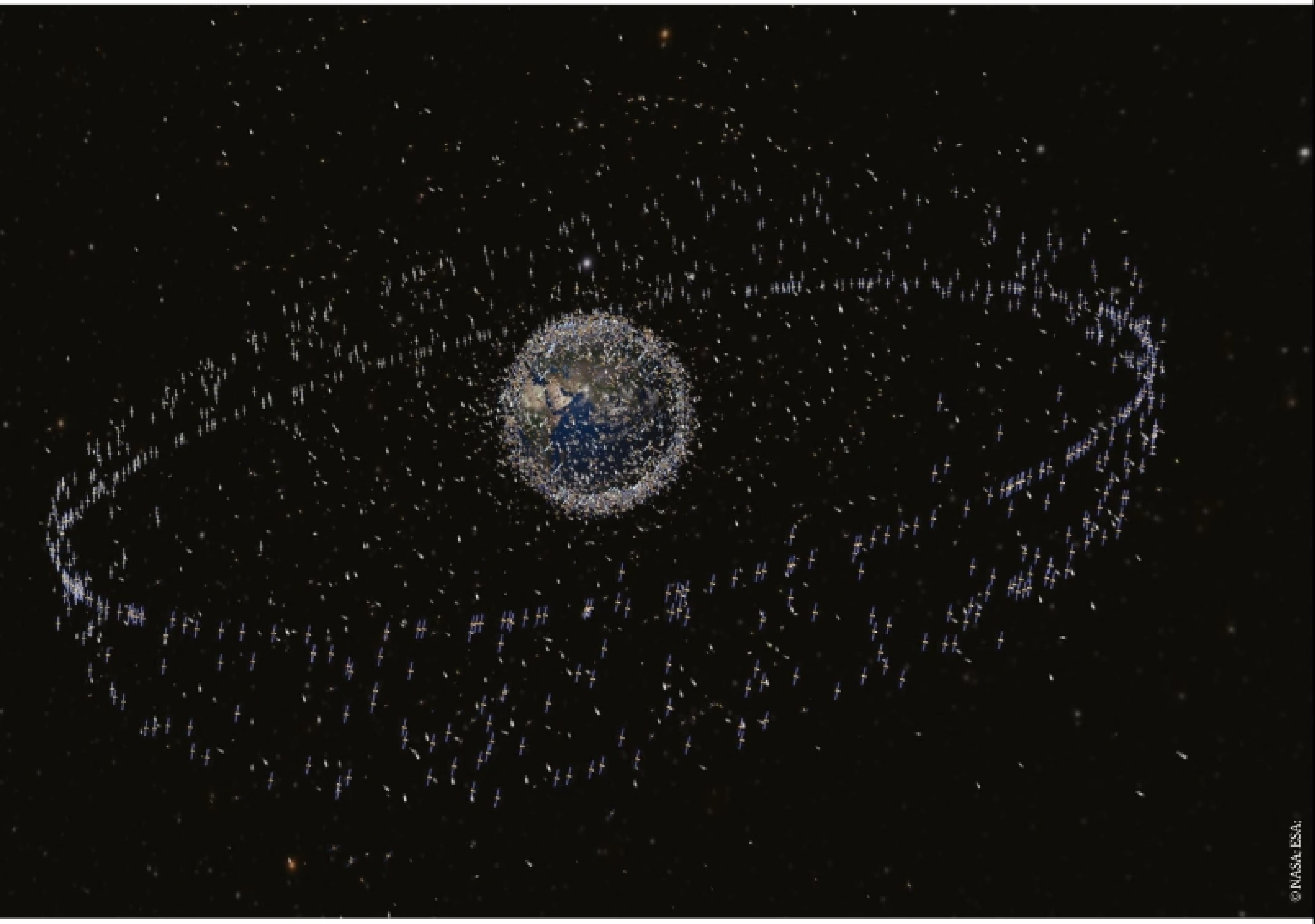
> "A lot of satellite operators choose not to worry about forecasts because they do not have sufficient accuracy" **Professor Chris Scott**

Clockwise, top left: A CME blasting from the Sun's surface in the direction of Earth

A massive sunspot around the size of Jupiter is identified by the SOHO spacecraft in 2003

Satellite operators have been warned of the dangers a large solar storm could pose

The Sun goes through a natural solar cycle every 11 years, composed of significant increases and decreases in sunspots and eruptions



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What if our Sun became too active?

With enough notice and preparedness we could negate the dangers and simply enjoy the greatest light show of all time

All eyes to the skies

If major solar activity were to threaten Earth, our solar science community and their legion of orbiters as well as land-based observatories would need to work out the likelihood, scale and arrival date of a direct hit.

Planes take the long way around

To avoid endangering staff and passengers with exposure to high radiation levels, operators of transatlantic flights would be encouraged to avoid usual 'over the poles' routes.

Astronauts take refuge

During an intense solar storm any planned spacewalks are cancelled and astronauts would be asked to set themselves up in the most shielded modules of the station.

Satellites switched to safe mode

If given sufficient notice of an incoming solar storm satellite operators would be encouraged to switch any orbiting units to safe mode.

Saving power

To avoid widespread blackouts power companies will need significant stocks of replacement transistors and crew deployed on the ground to tend to damaged parts of their grids

The greatest light show on Earth

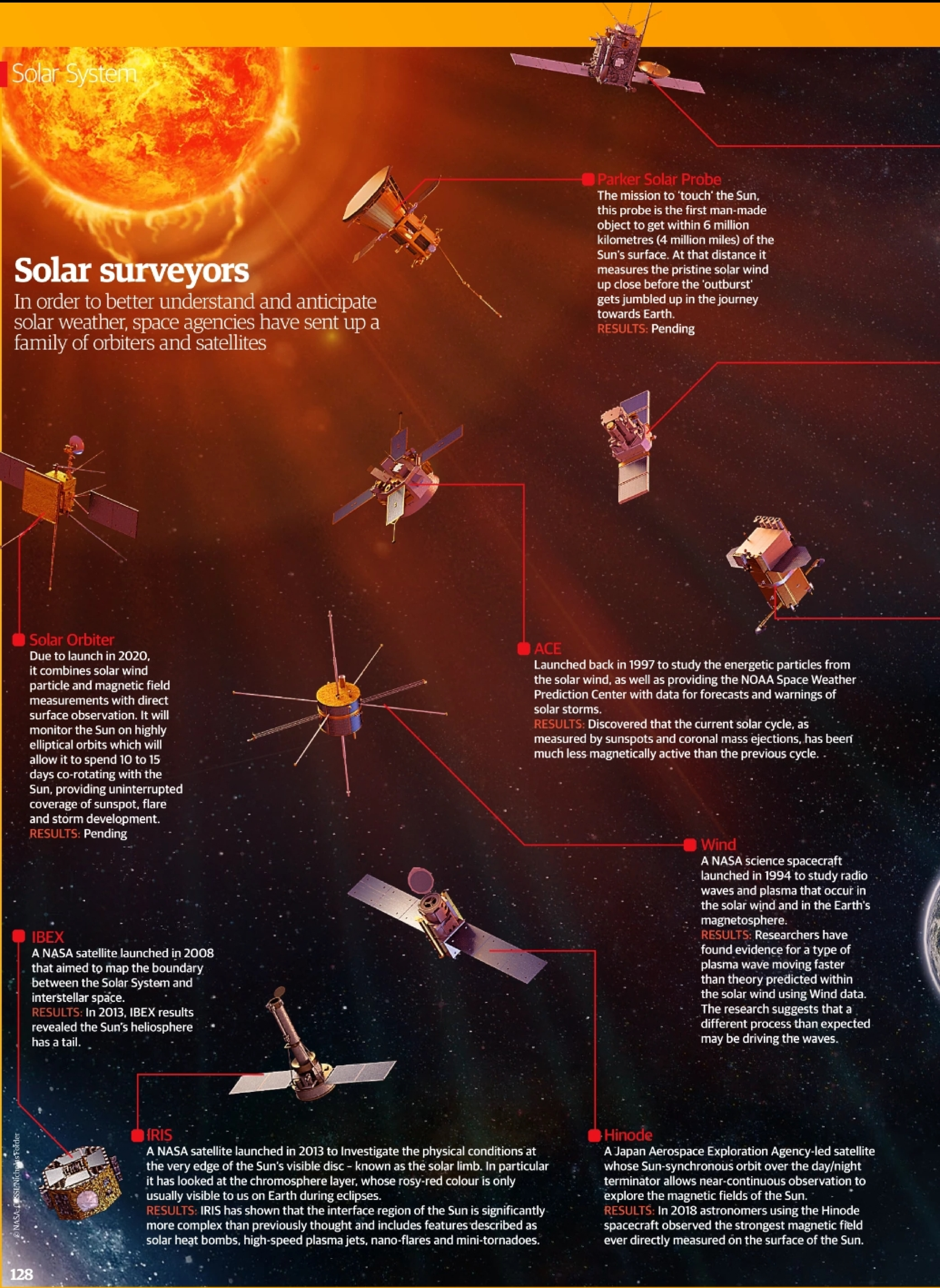
One positive effect of intense solar activity is the chance for more people to enjoy the northern and southern lights at much lower latitudes than usual are bathed in aurorae.

Solar surveyors

In order to better understand and anticipate solar weather space agencies have sent up a family of orbiters, satellites and probes.

Solar surveyors

In order to better understand and anticipate solar weather, space agencies have sent up a family of orbiters and satellites



Parker Solar Probe
The mission to 'touch' the Sun, this probe is the first man-made object to get within 6 million kilometres (4 million miles) of the Sun's surface. At that distance it measures the pristine solar wind up close before the 'outburst' gets jumbled up in the journey towards Earth.
RESULTS: Pending

Solar Orbiter
Due to launch in 2020, it combines solar wind particle and magnetic field measurements with direct surface observation. It will monitor the Sun on highly elliptical orbits which will allow it to spend 10 to 15 days co-rotating with the Sun, providing uninterrupted coverage of sunspot, flare and storm development.
RESULTS: Pending

ACE
Launched back in 1997 to study the energetic particles from the solar wind, as well as providing the NOAA Space Weather Prediction Center with data for forecasts and warnings of solar storms.
RESULTS: Discovered that the current solar cycle, as measured by sunspots and coronal mass ejections, has been much less magnetically active than the previous cycle.

Wind
A NASA science spacecraft launched in 1994 to study radio waves and plasma that occur in the solar wind and in the Earth's magnetosphere.
RESULTS: Researchers have found evidence for a type of plasma wave moving faster than theory predicted within the solar wind using Wind data. The research suggests that a different process than expected may be driving the waves.

IBEX
A NASA satellite launched in 2008 that aimed to map the boundary between the Solar System and interstellar space.
RESULTS: In 2013, IBEX results revealed the Sun's heliosphere has a tail.

IRIS
A NASA satellite launched in 2013 to Investigate the physical conditions at the very edge of the Sun's visible disc – known as the solar limb. In particular it has looked at the chromosphere layer, whose rosy-red colour is only usually visible to us on Earth during eclipses.
RESULTS: IRIS has shown that the interface region of the Sun is significantly more complex than previously thought and includes features described as solar heat bombs, high-speed plasma jets, nano-flares and mini-tornadoes.

Hinode
A Japan Aerospace Exploration Agency-led satellite whose Sun-synchronous orbit over the day/night terminator allows near-continuous observation to explore the magnetic fields of the Sun.
RESULTS: In 2018 astronomers using the Hinode spacecraft observed the strongest magnetic field ever directly measured on the surface of the Sun.

© NASA; ESA; Nicholas Forder

vulnerable parts of their grids, safe modes for their satellites, back-up routes for transatlantic airlines and safe houses for orbiting astronauts. However, today's rudimentary early warning systems make preparedness a significant economic risk.

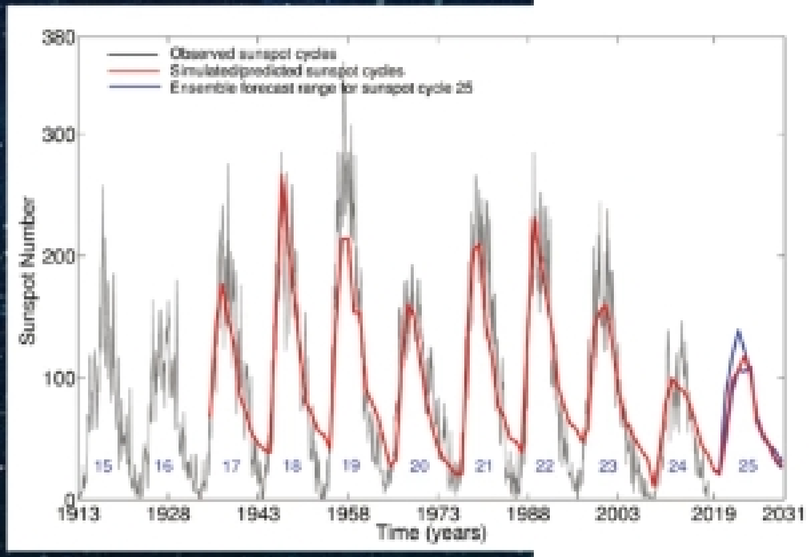
"A lot of satellite operators choose not to worry about space weather forecasts because they do not have sufficient accuracy to make it worth their while," says Scott, who calls for a new observation-focused mission to put a spacecraft out far enough to see the Sun and the Earth in the same field of view. It would be stationed near enough to us to provide continuous real-time observations.

Further notice could be provided by looking for signature surface behaviour that proceeds major eruptions. This is where two of the latest additions to the Sun's community of human-made companions could prove useful. O'Brien's ESA-funded Solar Orbiter mission is due to launch in 2020. It combines solar wind particle and magnetic field measurements with direct surface observation, all from inside the orbit of Mercury.

Key to the Solar Orbiter's ability to spot impending eruptions will be its highly elliptical orbit, which will allow it to spend 10 to 15 days co-rotating with the Sun, providing uninterrupted coverage of sunspot, flare and storm development.

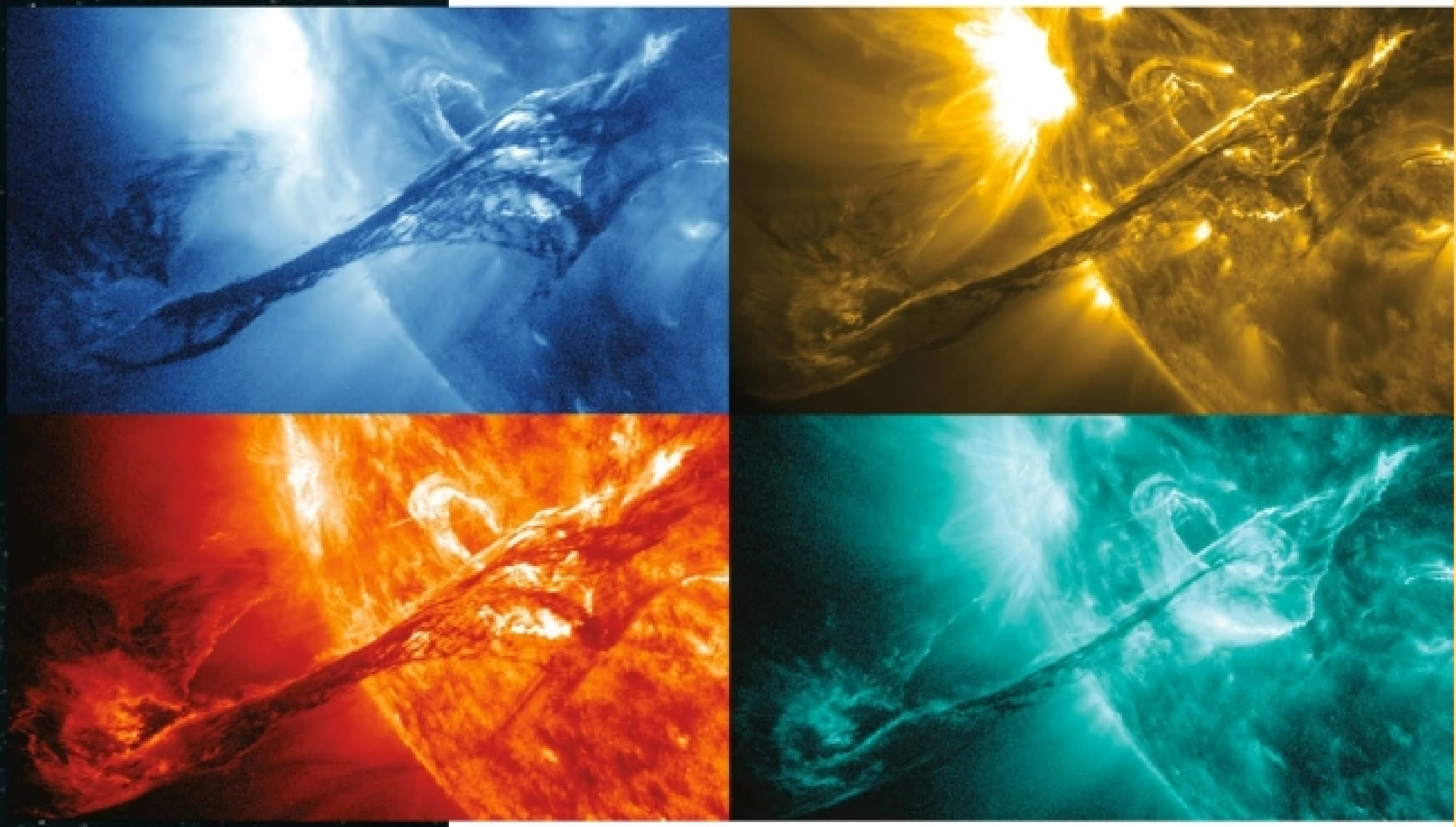
While the Solar Orbiter will take direct solar observation closer than ever before, NASA's Parker Solar Probe is pushing the boundary yet further. On its journey to 'touch' the Sun the probe will eventually fly as close as 6.1 million kilometres (3.8 million miles), meaning it will pass through the Sun's outer atmosphere.

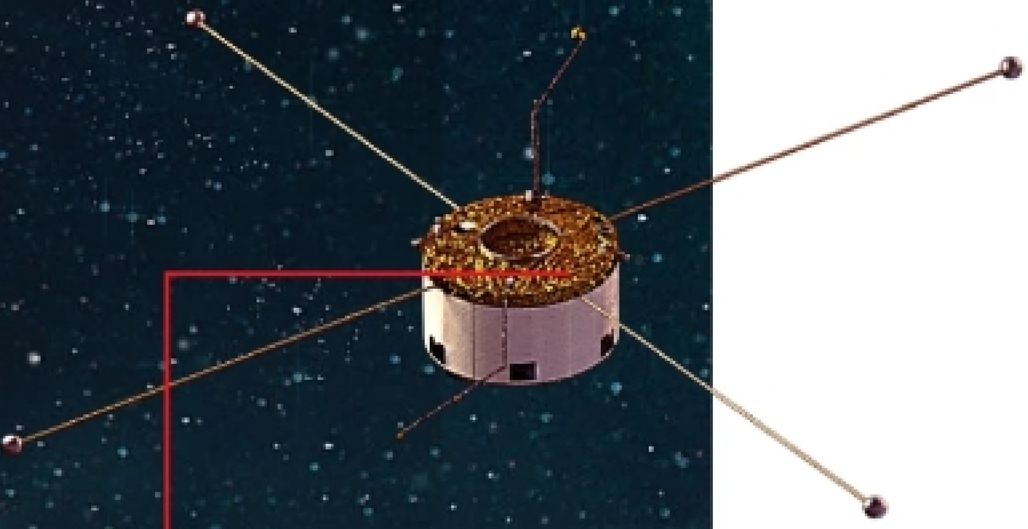
At that distance it hopes to measure the pristine solar wind – what it looks like when it leaves the Sun before it gets jumbled up in the 150-million-kilometre (93-million-mile) journey to Earth. "We will be able to couple together unprecedented details on what is happening on the dynamic, bubbling, boiling surface of the Sun with what is going in interstellar space," says O'Brien, who believes these new data sets and monitoring stations provide hope for our ability to give fair warning of future eruptions during the next solar cycle.



Above: Researchers have modelled the number of sunspots between 1913 and 2031

Below: The coronal mass ejection, viewed in four extreme ultraviolet wavelengths, in 2012 that sent a massive solar storm that just missed Earth





STEREO
Two near-identical spacecraft launched in 2006 into orbits around the Sun ahead of and behind the orbit of the Earth. This enables stereoscopic imaging to provide in-depth information when observing solar phenomena, such as coronal mass ejections.
RESULTS: One of the STEREO craft – STEREO A – was in the path of the solar storm of 2012 which was similar in strength to the Carrington Event. Its instrumentation was able to collect and relay a significant amount of data about the event.

SOHO
One of the original craft still in operation, SOHO was launched in 1995 and combines imagers and spectrometry instruments to probe the layered structure of the Sun with in-situ measurements of the solar wind as it goes past.
RESULTS: SOHO has also discovered over 3,400 comets as they orbit around the Sun, as well as providing the main source of near-real-time solar data for space weather prediction.

Solar Dynamics Observatory
Launched in 2010 to investigate how the Sun's magnetic field is generated and structured and how this stored magnetic energy is converted and released into the heliosphere in the form of solar wind, energetic particles and variations in the solar irradiance.
RESULTS: Has identified possible precursors to space weather in the behaviour of plasma within the regions encircling sunspots.

Cluster II
Launched in 2000, the Cluster II mission is an in-situ investigation of the interaction between the solar wind and the magnetosphere by using four satellites.
RESULTS: Has developed the first models of the Earth's magnetic field and its interaction with the solar wind based on actual measurements rather than theory.

DSCOVR
Originally proposed by then-Vice President Al Gore, DSCOVR monitors variable solar wind conditions and their impact on the Earth, including changes in ozone, aerosols, dust and volcanic ash, cloud height, vegetation cover and climate.
RESULTS: Took the second picture of the entire Earth, following on from the final Apollo mission's famous Blue Marble picture.

THE HU PLAN

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Could this hidden planet really exist? All About Space meets the scientists who could be on the trail of an undiscovered world

Reported by Jonathan O'Callaghan

© Tobias Roetsch

Astronomers have long wondered if our Solar System could contain a missing, unseen planet. A century ago some were convinced there was a gas giant lurking in the outer reaches, before later being derided for such a suggestion when it proved false. But now momentum is building that there may be another planet that has been hidden from our view and, while we haven't found it yet, we can see its fingerprints all over the outer Solar System.

This is Planet Nine, which was first seriously proposed by astronomers Mike Brown and Konstantin Batygin from the California Institute of Technology (Caltech) in 2016. Looking at the outer Solar System they noticed something odd – namely that several objects seemed to be grouped together, as if a more distant object was shepherding them into similar orbits with its immense gravity. After eliminating other possible explanations this led them to believe there must be a planet far beyond the orbit of Neptune: a real ninth planet after Pluto's demotion to dwarf planet.

"This world is the ninth true planet of our Solar System," Batygin tells **All About Space**. "We have never seen it directly, but we know it's there because of the gravitational signatures that it provides in the Solar System."

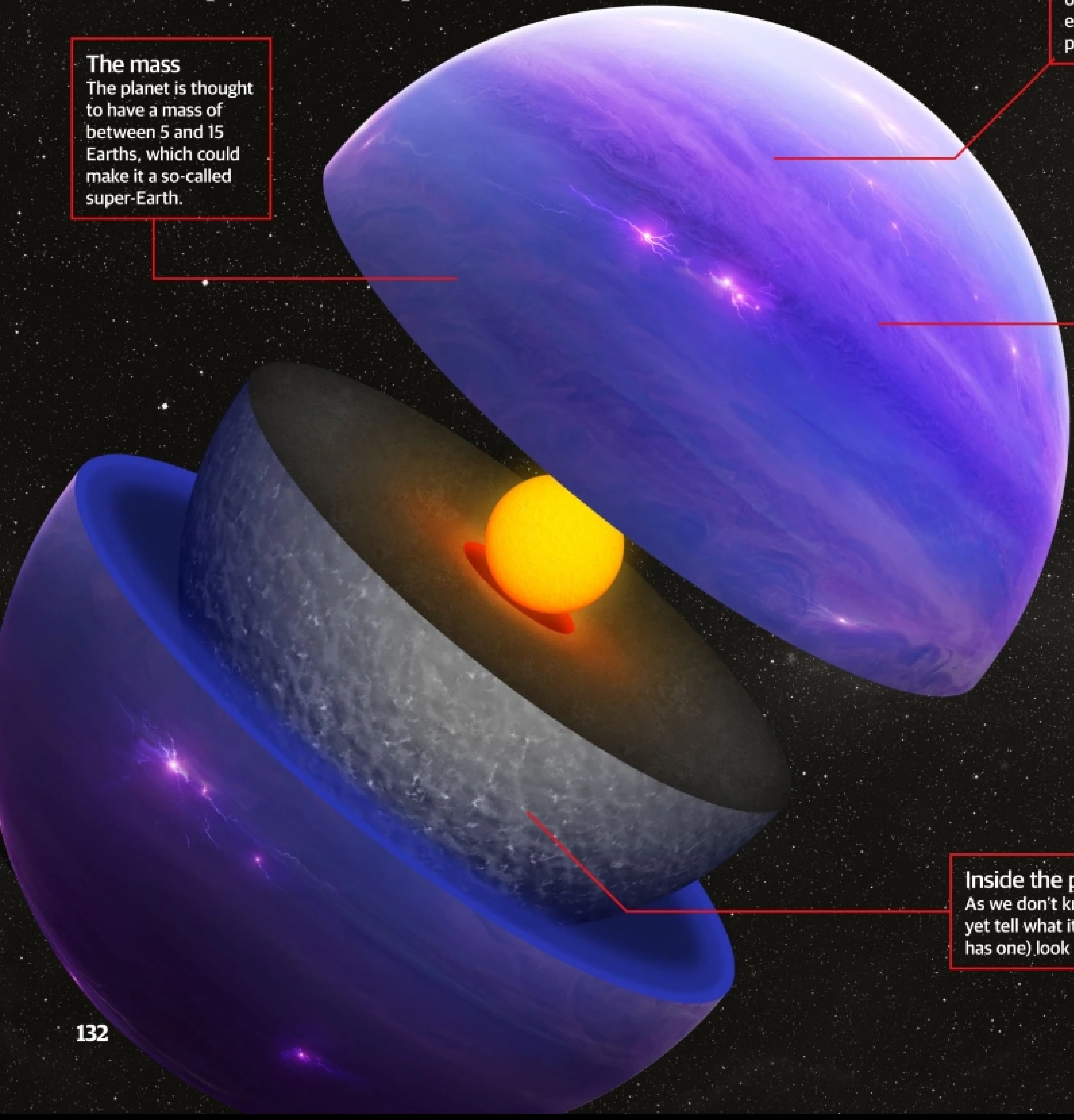
This is not the first time a planet beyond Neptune has been proposed. In 1906 US astronomer Percival Lowell was convinced there was a large planet hiding out there owing to Uranus appearing to orbit off course. He dubbed it Planet X – with 'X' referring to being unknown, rather than 'ten', as only eight planets were then known. So convinced was he that he founded the Lowell Observatory in Arizona to hunt for it.

The search for this Planet X was unsuccessful, but the Lowell Observatory did accidentally redefine the entire Solar System. In 1930 a young US astronomer called Clyde Tombaugh used the telescope to discover Pluto. At the time this sparked intense interest that this might be Planet X, but it was later found to be a small world roughly one-fifth the size of Earth, not nearly large enough to explain the orbit of Uranus.

The original Planet X was consigned to the bin, and the theory is now often scorned at, which might be why the idea of Planet Nine is so controversial. Batygin is pretty confident things will be different this time, however. "If you go back through the history of astronomy, the number of times that a trans-Neptunian planet [one beyond the orbit of Neptune] has been proposed is quite astonishing," he says. "The difference is that this

What could this other world be made of?

Here's what we know and don't know about the potential ninth planet



The mass
The planet is thought to have a mass of between 5 and 15 Earths, which could make it a so-called super-Earth.

Cold as ice
Being located beyond the orbit of Neptune, it's likely to be extremely cold – any water the planet has will be frozen as ice.

On the surface
If the planet is smaller than 1.6 Earth radii it might have a rocky surface. If it's larger, it could be more similar to a gas giant.

Inside the planet
As we don't know the planet's radius, we can't yet tell what its core, mantle or atmosphere (if it has one) look like.

time I think we're right." If they are right, here's what we know so far. Planet Nine is estimated to be about 5- to 15-times the mass of Earth, although we don't know its radius. Its eccentric 20,000-year-long orbit around the Sun may take it anywhere from as close as 200-times the Earth-Sun distance (200 Astronomical Units, or AU) to the Sun, and up to 1,200 AU away. Such a mass has earned the planet the moniker of super-Earth, a potentially large, rocky planet up to four-times the radius of Earth. But it could also be a mini-Neptune, a gas planet somewhat smaller than Uranus and Neptune.

While we can infer the existence of Planet Nine in the outer Solar System we can't yet see it, because if it's there it's extremely distant and faint. But astronomers are trying in earnest to find it as we speak. A number of surveys around the world, and more coming online in the future, are scouring the sky to look for any sign of a planet orbiting on its predicted path. And in doing so they are also finding other objects that lend further evidence that Planet Nine exists.

So far about a dozen such objects have been discovered, each clustered on a similar path on the same side of the Sun, including the possible dwarf planet Sedna found in 2003 that takes more than 11,000 years to orbit. The most recent was 2015 TG387, more colloquially known as 'The Goblin', which was first spotted in October 2015 and announced in October 2018 by Scott Sheppard from

Above: A passing star could also explain the orbits of the inner Oort Cloud objects

Right: The Blanco Telescope has been instrumental in the search for Planet Nine

"We have never seen it directly, but we know it's there because of the gravitational signatures" **Konstantin Batygin**

©T.A. Rector (University of Alaska Anchorage) and H. Schweiker (WIYN and NOAO/AURA/NSF); Tobias Roetsch; David walker

the Carnegie Institution for Science and his colleagues. Thought to be a dwarf planet about 300-kilometres (186-miles) across and orbiting the Sun every 40,000 years, The Goblin is yet another piece in the puzzle that Planet Nine exists.

"The Goblin continues the trend seen in the past for this planet that we think is out there," Sheppard tells **All About Space**. "If it matches our predictions, then The Goblin is stable to its orbit, and it kind of dances with the planet."

Objects like The Goblin are given a specific moniker: inner Oort Cloud objects. They are found in a region between the Kuiper Belt and the Oort Cloud, the former extending from 30 to 55 AU and the latter anywhere from 2,000 to 200,000. This region, notes Sheppard, is a 'no man's land' where the objects are too far away to be affected by the eight known planets, but still bound to the Sun and oblivious to outside forces like other stars or the supermassive black hole at the centre of our galaxy.

Only a dozen such objects have been found so far, but the number could be higher. Much, much higher. It's estimated that thousands of these objects larger than 50 kilometres (30 miles) in size, or even perhaps millions, could be in orbit around the Sun. As their orbits are very elongated, however, they spend most of their time far away, only brightening and becoming visible when they approach the Sun. "We're just seeing the tip of the iceberg," says Sheppard.

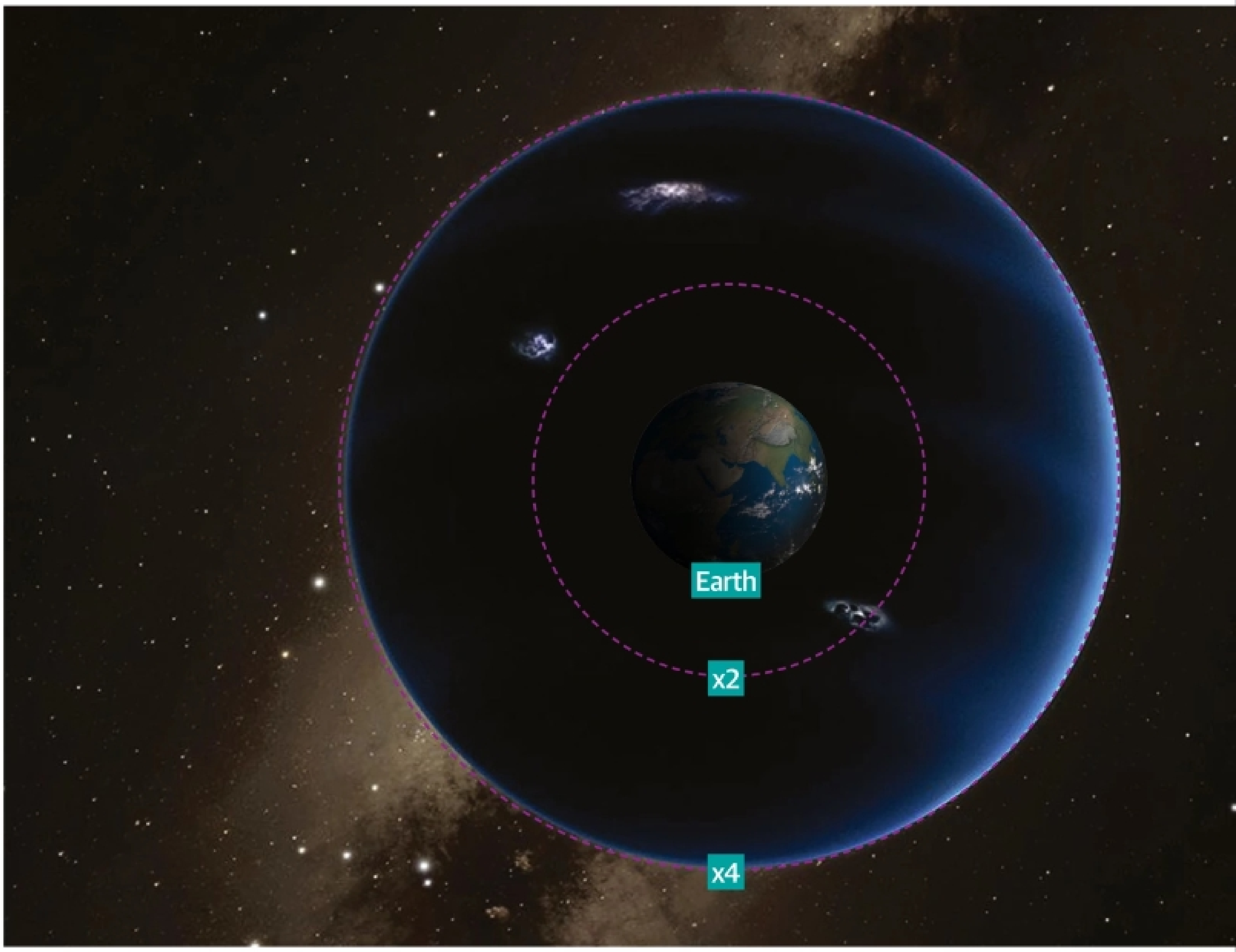
Not everyone is convinced these objects are proof of another planet, however. There are other explanations that, with a bit of fiddling, can explain how they cluster together, and the theory of Planet Nine is anything but widely accepted just yet. "You can do this with a flyby of another star or a brown dwarf, a massive object early in the Solar System's history," says Michele Bannister from Queen's University Belfast. "Potentially [there are] also some physical processes that involve how the objects interact with the inner Oort Cloud and the tide of the galaxy. [Or] Neptune [could] perturb some of these objects over hundreds of millions of years."

In mid-2018 a team led by Ann-Marie Madigan from the University of Colorado, Boulder proposed an additional possibility. They say the natural

Above: Sedna was the first body found in the Solar System's "no man's land"

Below: If it exists, Planet Nine could be 2- to 4-times the size of Earth

> "The main goal right now is finding more of the smaller objects that can lead us to the bigger one" **Scott Sheppard**



Clues to another world's existence

Clustering of objects

A dozen objects in the outer Solar System seem to be clustered together, with their closest points to the Sun all being fairly similar. This suggests there is a large unseen mass – a planet – shepherding their orbits.

The same side

Not only do those 12 objects have a similar perihelion, but they are also all grouped on one side of the Sun. Again, this suggests there is something out there pulling them in that direction.

The wrong way

Some objects in the outer Solar System appear to be orbiting in the opposite direction to everything else, perhaps being pulled into these extremely elliptical orbits by Planet Nine.

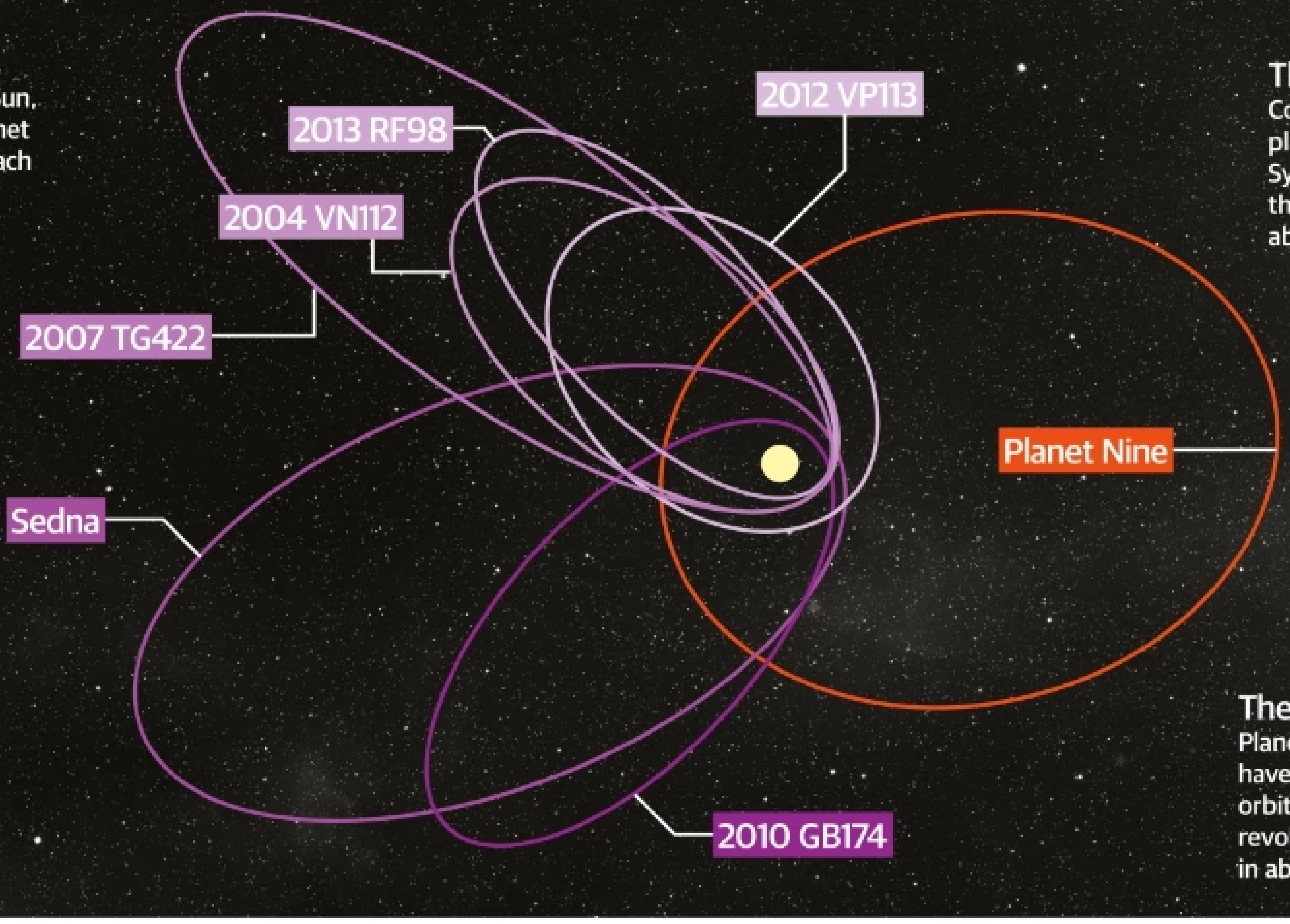
The missing super-Earth

Many other planetary systems we've found in our galaxy contain a super-Earth. Could Planet Nine be the missing planet from our Solar System that's common almost everywhere else?

© LSST Project Office, Caltech

Planet Nine's orbital path

How we think this world dances around the Sun



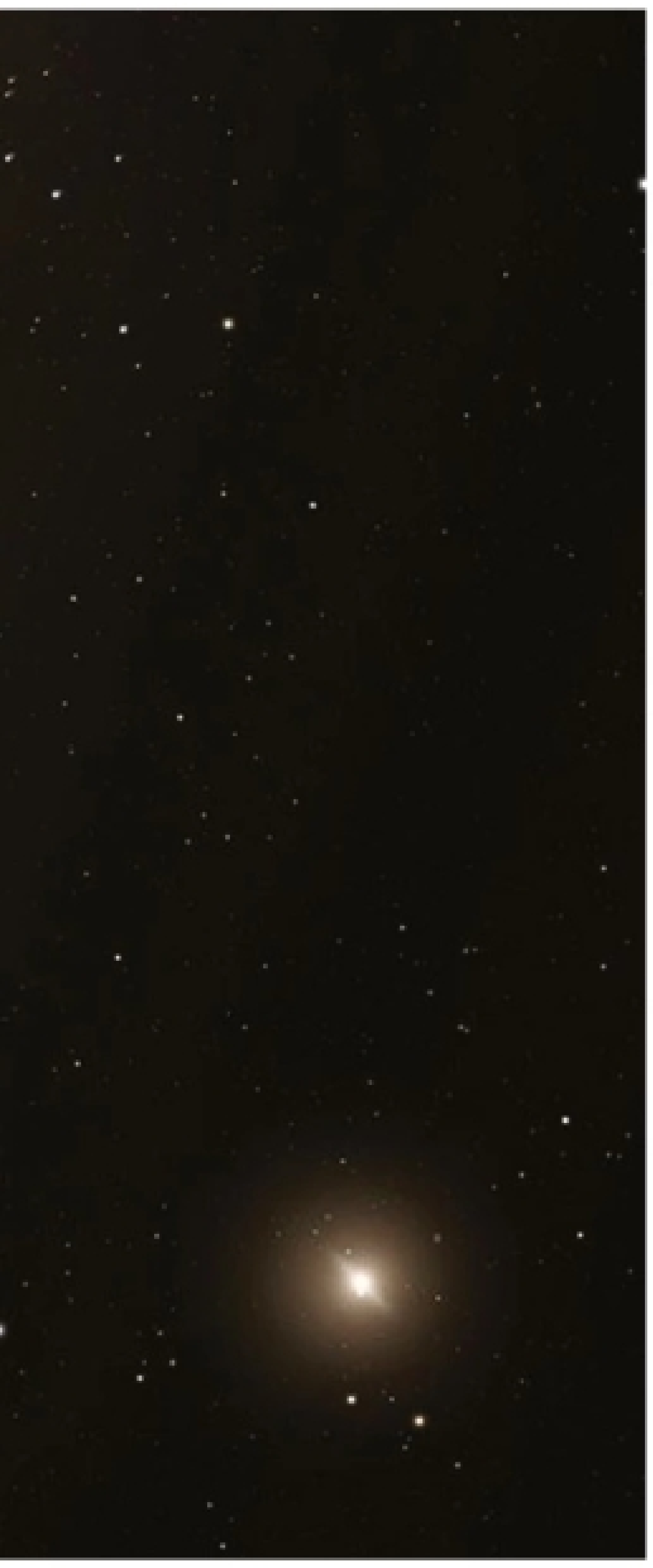
The next-nearest planet
Neptune's orbit only takes it out to about 30 AU, more than six-times less than the perihelion of Planet Nine.

Closest point
At its closest point to the Sun, known as a perihelion, Planet Nine is predicted to approach to about 200 AU away.

The inclination
Compared to the other planets of the Solar System Planet Nine is thought to be inclined by about 30 degrees.

Farthest point
Planet Nine's orbit is thought to extend out to a distance of up to 1,200 AU from the Sun into the far outer Solar System.

The shape of its orbit
Planet Nine is thought to have a highly eccentric orbit, completing one revolution around the Sun in about 20,000 years.

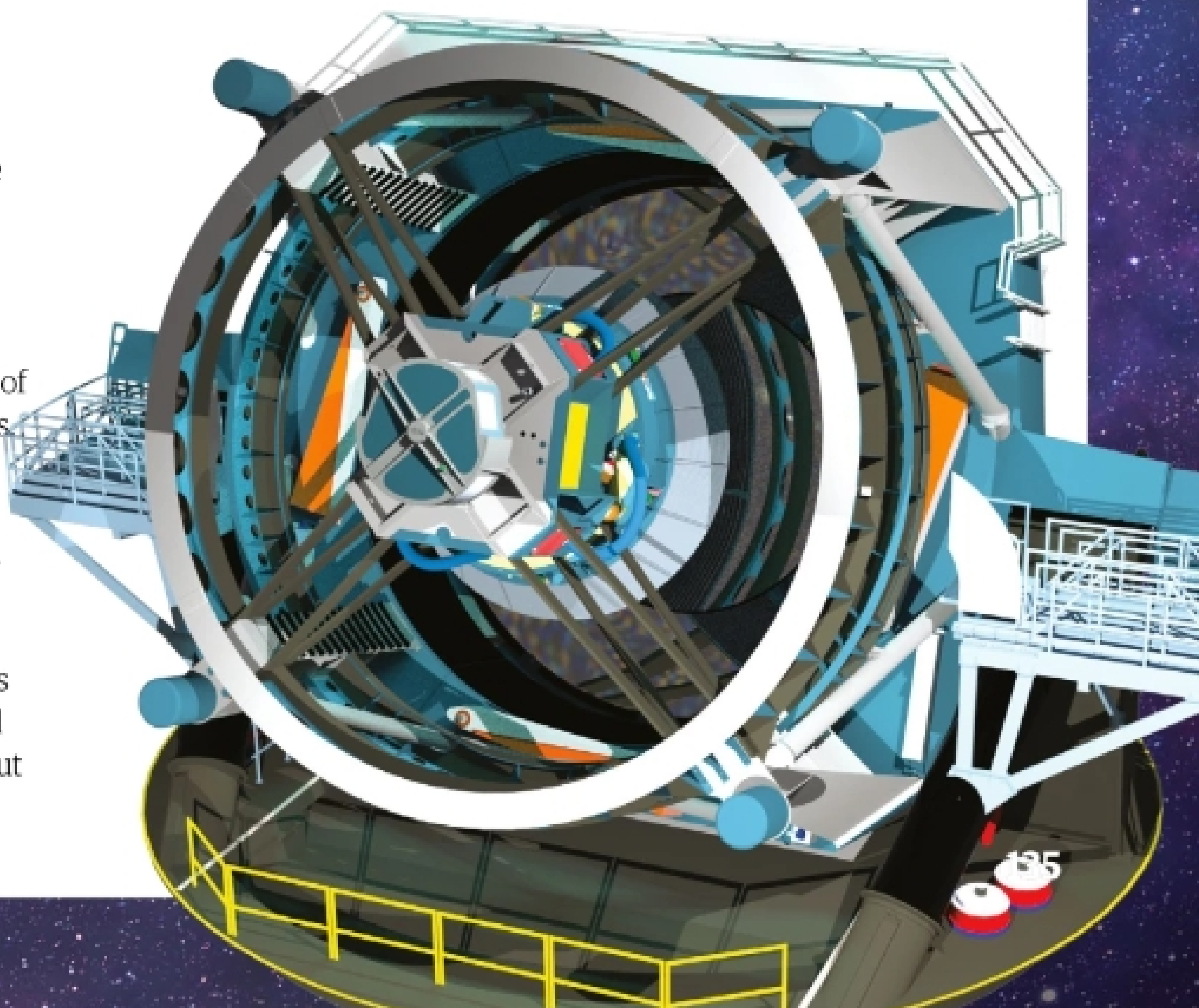


jostling of the dozen inner Oort Cloud bodies found so far, and space debris in the outer Solar System, could explain their orbits. The collective gravity of the bodies, they say, could provide an answer as to why they clustered together.

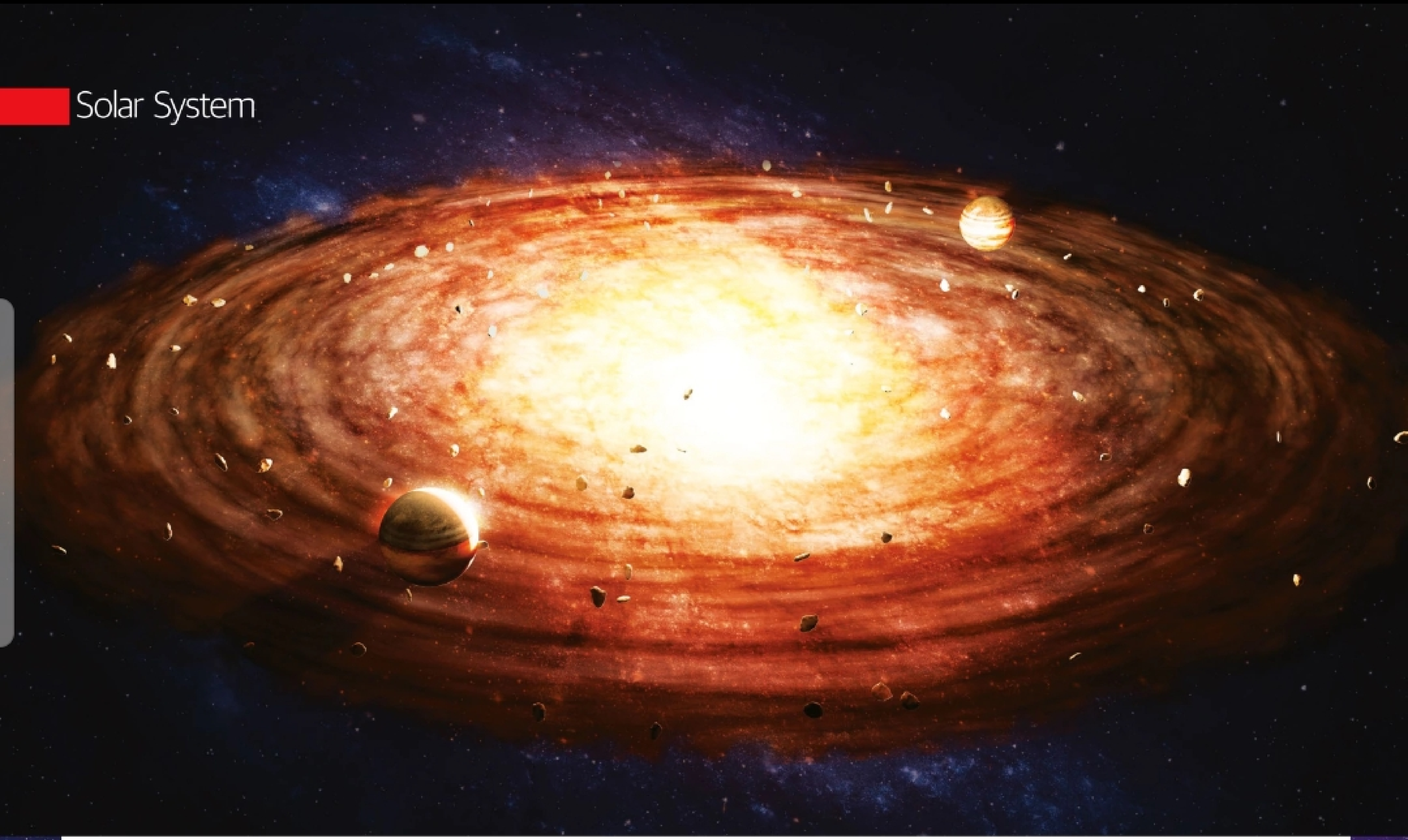
The main issue is that these dozen bodies we have discovered so far shouldn't really be there. "They are small bodies in the outer Solar System that shouldn't exist," says Megan Schwamb from the Gemini Observatory in Hawaii. And that has led to the suggestion of Planet Nine, but it doesn't mean that is the only explanation. "The same evidence for is also the same evidence against," says Schwamb. "You could have formed these objects detached from Neptune in a stellar cluster. Early on in the Sun's history many stars coming within 500 to 1,000 AU would have stirred up objects and would have been able to detach them from the outer Solar System and put them in these eccentric orbits. Other options are a single star passing by, or rogue planets leaving the Solar System."

Getting to the answer will be no mean feat, but answers may be forthcoming rather soon. At the moment our observations and data for this region of the Solar System come mostly from two telescopes, the Subaru Telescope in Hawaii for the northern sky, and the Blanco Telescope in Chile for the southern sky. Observations were especially helped by the installation of the Dark Energy Camera (DECam) on the Blanco Telescope in 2012. "Up until 2012 it was like looking through a straw," says Sheppard. "In 2012 the game changed and allowed the floodgates to open for this kind of research." But even together these two telescopes can see only a small patch of the sky, with about 20 per cent of the sky observed to date, and as the inner Oort Cloud objects are so far away and so faint, they're extremely hard to see.

The game is going to change again though in 2022, when a new telescope called the Large Synoptic Survey Telescope (LSST) comes online in Chile. Although predominantly designed to find near-Earth asteroids, the LSST will also be able to find more objects in the outer Solar System, covering about 70 per cent of the sky in total. And if there are thousands or millions of objects out there as thought, then there could be a whole swathe of worlds – and possibly more evidence for or against



The Large Synoptic Survey Telescope could narrow down Planet Nine's location from 2022



Planet Nine – awaiting our discovery. "Though we want to find the planet, the main goal right now is finding more of the smaller objects that can lead us to the bigger one," says Sheppard. "If we can double that number, we can start limiting where the planet can be."

After that the next big step will be actually seeing Planet Nine. Scientists are already poring through images of the outer Solar System hoping to spot its faint glint but, without knowing its exact location, such efforts are extremely difficult. If it were at its point nearest the Sun right now it would likely already have been spotted owing to its brightness, so if it exists it is more likely much farther out in the Solar System near the outer point of its orbit, known as aphelion, where it also moves at its slowest speed. So far, mostly using the Subaru Telescope, efforts to find the planet have been unsuccessful, but the hunt continues.

Until then, Planet Nine will continue to be hotly contested. While some are convinced it exists, others are not quite ready to throw their hat in the ring just yet, with memories of Planet X and other faux worlds no doubt fresh in the mind. "I'm agnostic about whether it's a planet or not," notes Schwamb, while Sheppard says he is "80 to 85 per cent sure" it exists. But if all the stars – or should we say, inner Oort Cloud objects – align, then perhaps there really is a missing super-Earth hiding. "I don't think we're going to find it next week, but at the same time I don't think it's going to take 20 years to find this thing," Batygin says resolutely.

Above: Planet Nine could give a new insight into how our Solar System formed

Below: Scientists are using the Subaru Telescope in Hawaii to hunt for Planet Nine

Debate: Is it likely that another planet exists?

Scientists are conflicted about the existence of a ninth Solar System member

Yes

If another world is not there you need other theories to explain each of the anomalous patterns we see. You need a theory to explain why the orbits are aligned together, a theory to explain why objects are out of the reach of Neptune and another to explain why some orbits get flipped upside down. Another planet explains all of these anomalies consistently.

Konstantin Batygin, California Institute of Technology

No

A small group of us are working on an alternative hypothesis which involves the collective gravity of minor planets. These minor planets orbit so far away from the Sun and the major planets that the weak gravity acting between them can build up slowly over time and come to dominate their dynamical evolution. They can rearrange their own orbits into a distribution similar to what we observe in the outer Solar System without the need for another planet. This explanation predicts that there is a disc of minor planets more massive than the Kuiper Belt awaiting discovery at hundreds of AU.

Ann-Marie Madigan, University of Colorado, Boulder

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> "It's likely to be quite some years before the dark energy riddle is solved"

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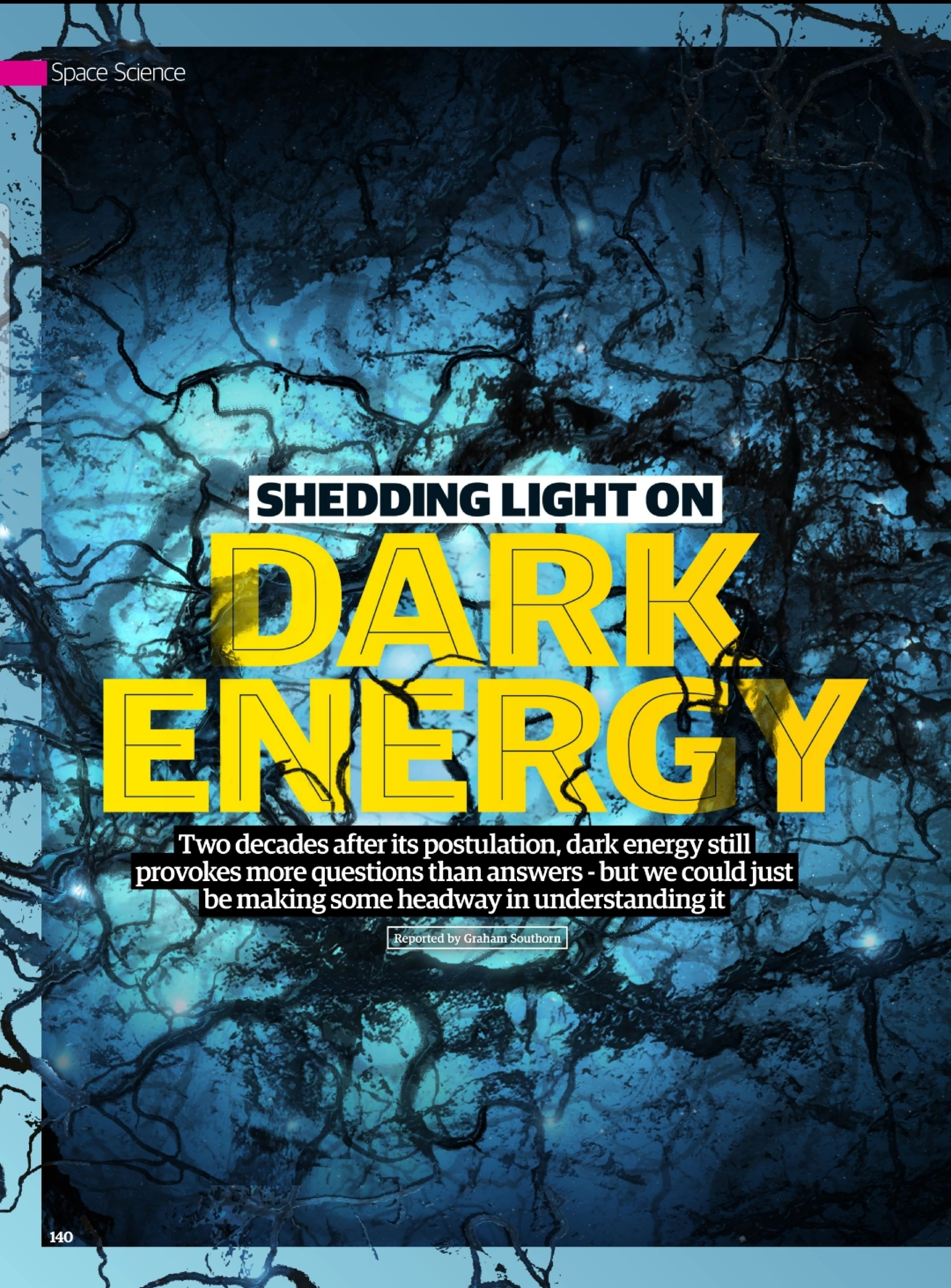


SHEDDING LIGHT ON DARK ENERGY

Two decades after its postulation, dark energy still provokes more questions than answers - but we could just be making some headway in understanding it

Reported by Graham Southorn

© Tobias Roetsch

Two decades ago, astronomers studying distant stars made a dramatic discovery. They were investigating the future of the universe, which was known to be expanding. Contrary to all expectations they discovered that the rate of expansion was actually speeding up – the universe was getting bigger, and faster. Today the focus is on finding the cause of this unexplained phenomenon, which has been given a suitably mysterious moniker: 'dark energy'.

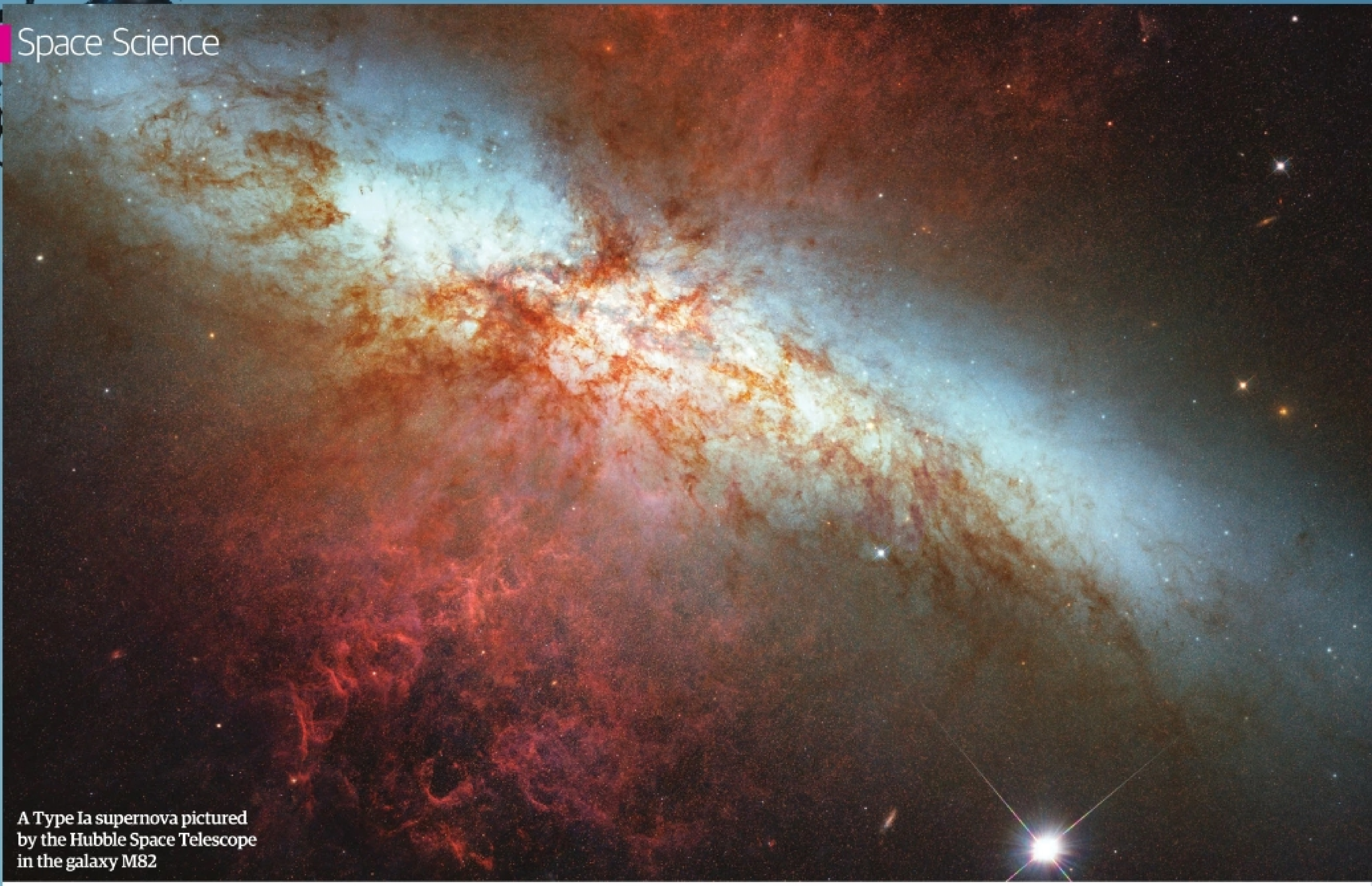
The discovery that the universe was expanding ever faster came as a huge surprise. In fact, it was so significant that it led to the award of a Physics Nobel prize in 2011 to Saul Perlmutter, Brian P Schmidt and Adam G Riess.

These were the leading scientists from two competing teams who studied light from a particular type of exploding star – and lots of them. Type Ia supernovae flare up in a predictable way, so their relative brightness reveals how far away they are. Their redshifts – the elongation of wavelengths towards the red end of the spectrum – showed that it was those furthest away that were receding the fastest.

It was the opposite to what most scientists expected, says Robert Crittenden, professor of cosmology at the University of Portsmouth. "We'd always assumed that because gravity was attractive, the rate of expansion would be slowing down. Distant galaxies would be gravitationally attracted to each other and that would be slowing down the expansion of the universe," he says.

The discovery that the universe was expanding faster than before begged a question: what was causing it? The simplest solution, which many scientists still believe will ultimately prove to be the correct one, is decades old. It comes from Albert Einstein's general theory of relativity, which describes how gravity operates.

Before he published it in 1917, Einstein wrestled with one of its predictions. He believed that the universe was static, and yet the general theory of relativity predicted it would either expand or contract. In order to keep things in balance, he added a term to the equations: the famous cosmological constant.



A Type Ia supernova pictured by the Hubble Space Telescope in the galaxy M82

It was effectively a fudge, and it wouldn't last long. By the 1930s Edwin Hubble's observations of distant galaxies had shown that the universe wasn't static at all, but was expanding, and so Einstein abandoned the cosmological constant, reportedly calling it his "biggest blunder".

In the 21st century, though, the cosmological constant is back as the leading explanation for dark energy. In physical terms it's a number that describes the energy density of empty space. Even a perfect vacuum, devoid of any particles, is not devoid of energy. As the universe expands and more space is created, there's more energy to push things outward. This isn't hypothetical. There's a physical mechanism that explains where the energy comes from which can be found in another branch of physics: quantum mechanics. It says that temporary particles pop in and out of existence – a phenomenon that's been observed in particle experiments on Earth.

There's just one very big problem. Quantum calculations have produced a number for the energy density of empty space, but it's way, way bigger than what's required. "The cosmological constant is a very simple model, but when you try to relate it to fundamental physics the value you get is arguably 100 orders of magnitude different from what you expect. Apart from that it works very well in explaining what we see, but because of that problem people look at other ways to solve the riddle," says Crittenden.

One of the other ways of explaining dark energy is an energy field that isn't constant. Rather, it's dynamic. Its value changes over space and time, driving the expansion of the universe differently now compared to how it did in the past. The universe may have been born a long time ago – 13.8 billion years ago at the Big Bang – but dark energy has only come to dominate the expansion for the past 5 billion years or so.

There are many variations of this idea, which goes by the name of quintessence, or 'fifth force'. In physics terminology it would be a 'scalar field', similar to the Higgs field. And just as the Higgs field has an associated particle – the Higgs boson – so would the scalar field be responsible for dark energy.

A particle that could be responsible for dark energy has never been detected, but strangely enough this non-detection works in its favour as an explanation. Out in the far-flung reaches of the universe the field would be strong enough to fling galaxies apart, but in the presence of other masses around it, like in laboratories on Earth, the force it exerts would be miniscule.

One such hypothetical particle is called the chameleon. It can change its mass depending on the density of its surroundings, explains Clare Burrage, associate professor at the University of Nottingham. "Chameleons can self-camouflage. They can learn about their environment and adjust

The Victor M Blanco telescope in Chile captures light for the Dark Energy Survey

© NASA; LSST Camera Project ; Ross Cawthon; 2017 The Regents of the University of California, Lawrence Berkeley National Laboratory/Marilyn Chung

their properties so that the modification of gravity is hidden from experiments. But they can't hide from everything, so if you do a suitably chosen experiment you might be able to see its effects. We're using a technique called atom interferometry that's really sensitive to these forces."

The chameleon force would be exerted solely by the outer shell of an object rather than, say, gravity on Earth, which is exerted by the entire planet. This idea explains why the force would be so weak and why the experiments, which involve detecting the motion of atoms in free fall, needs to be super-sensitive.

"One of the interesting things about these theories is that you can design an experiment on Earth that might make their effects show up. It doesn't need to be in a huge particle collider. You just need to do the right kind of really sensitive measurement, using equipment that could fit on a couple of table tops. It's done on a small scale on a reasonably short timescale - a very different way of studying dark energy than launching a telescope, which can take decades," says Burrage.

The University of Nottingham team has yet to publish its results, and a group using the same technique at the University of California, Berkeley, has yet to spot anything unusual.

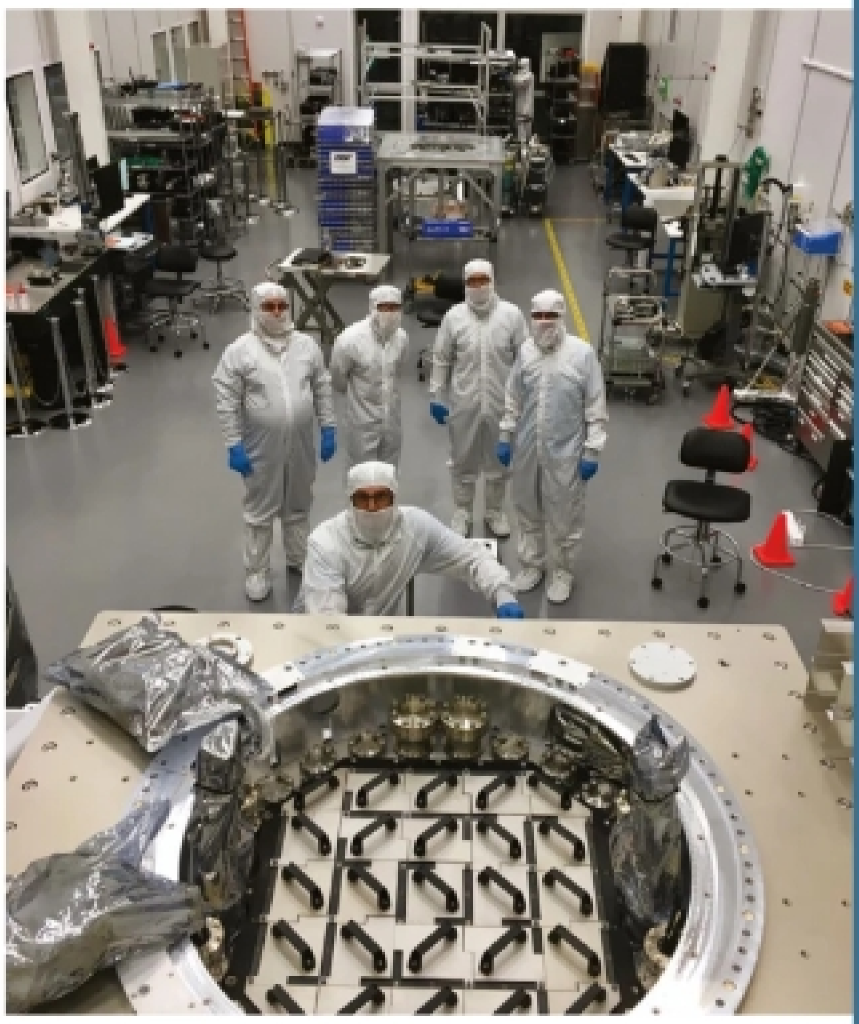
While physicists look for tell-tale signs in the lab, many astronomers have focused on making more precise maps of how the universe has evolved over time. One kind of map that's particularly important reveals the location of not just ordinary matter, of the kind that constitutes stars and planets, but dark matter too.

Dark matter is another cosmic mystery all by itself - an invisible form of matter that, like dark energy, has evaded detection. But while the particles making up dark matter have yet to be identified, its effects are clearly visible. Crittenden explains: "We've known about dark matter for a while longer than dark energy, and we need it on a smaller scale than the universe [as a whole]. Visible matter isn't nearly enough to explain the dynamics of stars around galaxies and galaxies around clusters of galaxies - we need a significant amount of dark matter as well."

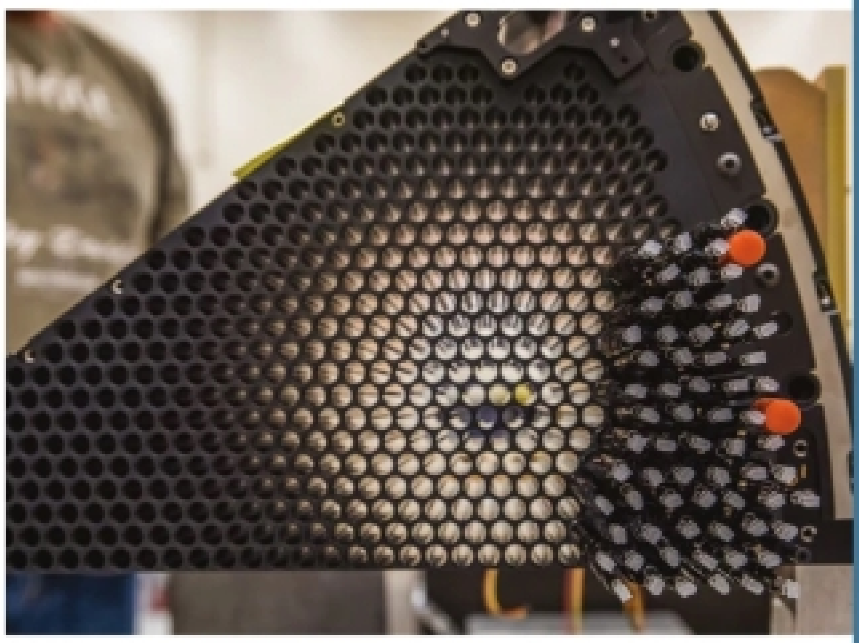
The currently accepted model of the universe holds that it's geometrically flat. And if this is so then dark matter must account for a staggering 27 per cent of all its mass-energy. Ordinary matter would make up just 5 per cent and the remaining 68 per cent would be dark energy.

However, dark matter and dark energy don't behave in the same way, says Crittenden. "Dark matter is generally attractive - it's like ordinary matter in how it gravitates. Dark energy has a very different effect - it doesn't cluster galaxies together and it's difficult to see its effect on individual galaxies."

Whereas dark matter acts to pull galaxies together, dark energy tries to pull them apart. This is where dark matter comes into play in the search



Cooling device for the world's largest digital camera - part of the Large Synoptic Survey Telescope



The fibres of the DESI can capture 5,000 galaxies simultaneously

> "Visible matter isn't nearly enough to explain the dynamics of galaxies around clusters of galaxies" **Prof Robert Crittenden**

What is dark energy?

What do scientists think the mysterious phenomenon is?

If you pressed me I'd go for the accelerated expansion of the universe being driven by a new kind of scalar field.

Prof Catherine Heymans, University of Edinburgh

If forced to bet I'd go for the cosmological constant - I think you'd get low odds for anything else!

Dr Thomas Kitching, Mullard Space Science Laboratory, UCL

Nothing works perfectly so far. My bet would be that we haven't thought of what will prove to be the right answer.

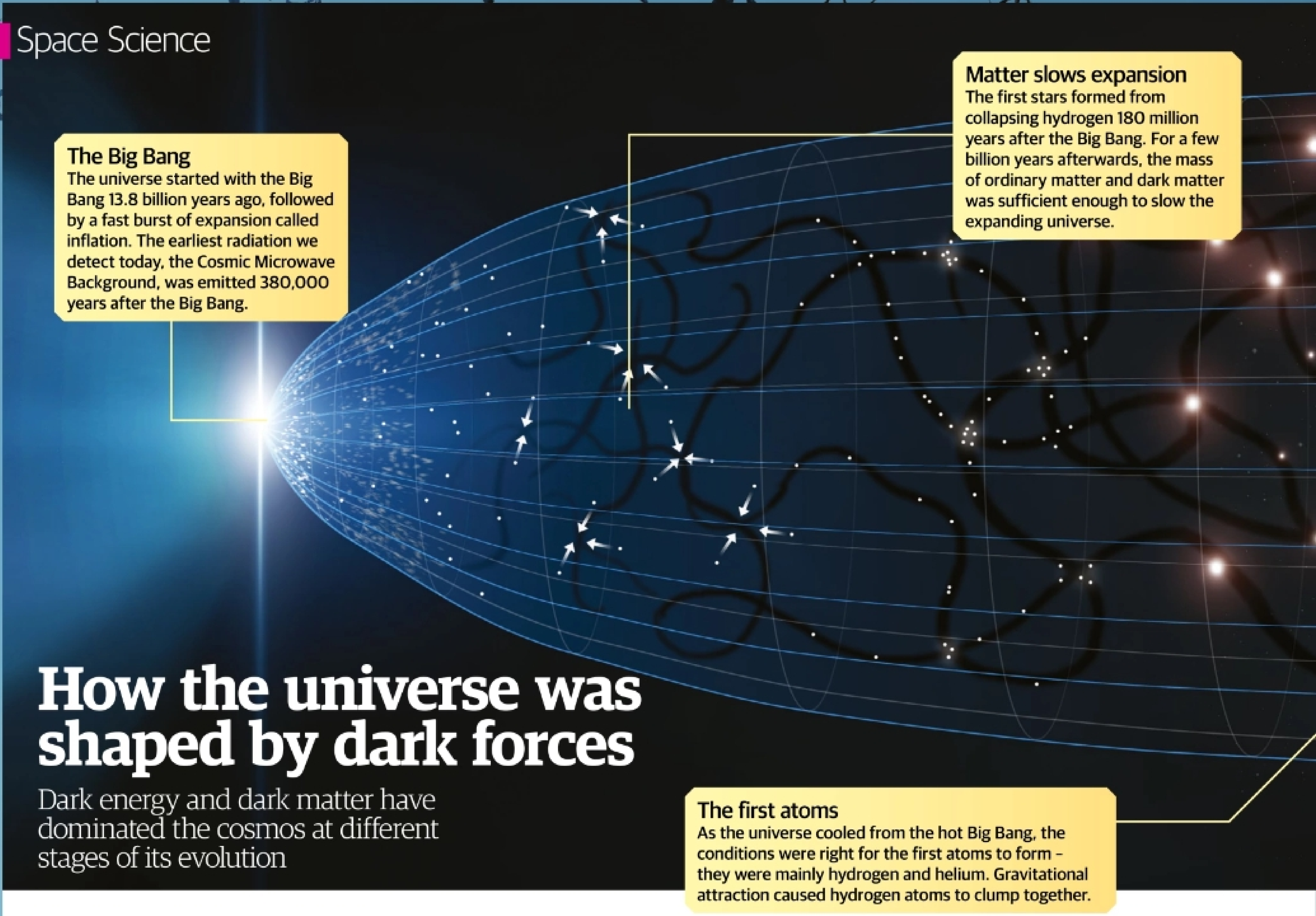
Dr Clare Burrage, University of Nottingham

What we see is consistent with the cosmological constant, with the big caveat of its magnitude.

Prof Robert Crittenden, University of Portsmouth

How the universe was shaped by dark forces

Dark energy and dark matter have dominated the cosmos at different stages of its evolution



The Big Bang
The universe started with the Big Bang 13.8 billion years ago, followed by a fast burst of expansion called inflation. The earliest radiation we detect today, the Cosmic Microwave Background, was emitted 380,000 years after the Big Bang.

Matter slows expansion
The first stars formed from collapsing hydrogen 180 million years after the Big Bang. For a few billion years afterwards, the mass of ordinary matter and dark matter was sufficient enough to slow the expanding universe.

The first atoms
As the universe cooled from the hot Big Bang, the conditions were right for the first atoms to form – they were mainly hydrogen and helium. Gravitational attraction caused hydrogen atoms to clump together.

for dark energy. By looking at what happens to large structures like clusters of galaxies over time, astronomers hope to learn how dark energy has influenced the evolution of the universe. "It's harder for structures to collapse when the background is expanding or accelerating because dark energy slows down the collapse, and that's the signature we're looking for," explains Crittenden.

So how are these maps made? One method is to look at how clumps of mass distort light as it passes by, a technique called gravitational lensing. An upcoming space telescope called Euclid will use the technique to find dark matter, explains Thomas Kitching, an associate professor at University College London's Mullard Space Science Laboratory and a manager in the Euclid project.

"As light from a galaxy passes through dark matter it gets distorted and bent. If you measure the change in shape you can determine how much dark matter is there, and you can use that to make a dark-matter map of the universe. You can then see how it's evolved over time. The way dark matter has evolved over time depends on what dark energy is," he explains.

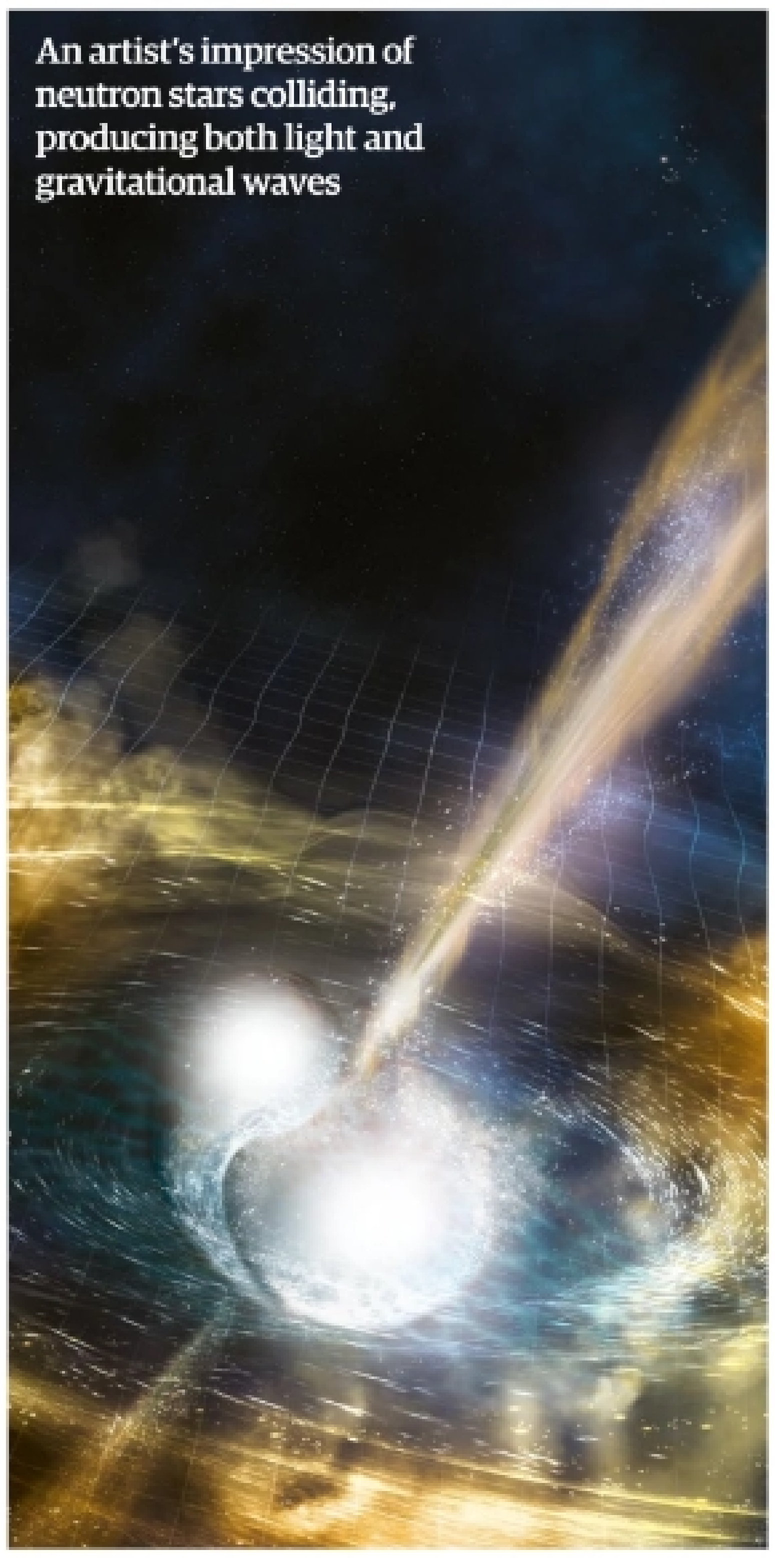
The lensing technique has also been used by astronomers involved in a collaboration called the Kilo-Degree Survey (KiDS), which has used images of the southern sky taken by the Very Large Telscope (VLT) in Chile.

At the University of Edinburgh, Ben Giblin is involved in the KiDS collaboration: "We've measured the amount of matter in the universe and the structure of this matter, and therefore we've indirectly measured dark energy. We've made one measurement, but other people have been observing a very different source – Cosmic Microwave Background (CMB) radiation, which is energy left over from the very early universe. We've come to slightly different conclusions. It's not like we completely disagree, but it's enough of a disagreement to make you scratch your head," he says.

"There's also a disagreement between the scientists who work on CMB and those who study the expansion of the universe with supernovae," he continues. "This maybe adds a little more fuel to the fire that, because we disagree and we're all using the same theory of gravity that involves the cosmological constant, maybe the whole theory of gravity is wrong. But there's not strong enough evidence for that at this point."

The way out of this impasse is to gather more data, and there's certainly more on the way. The Dark Energy Survey, an international collaboration in which the University of Portsmouth is involved, is coming to the end of its five-year mission and is set to release more data. In addition, a new detector, the Dark Energy Spectroscopic Instrument (DESI), will begin examining redshifts to determine the collapse rate of large structures in 2019.

Beyond that, a giant new instrument called the Large Synoptic Survey Telescope will produce the most detailed wide-field survey to date using



An artist's impression of neutron stars colliding, producing both light and gravitational waves

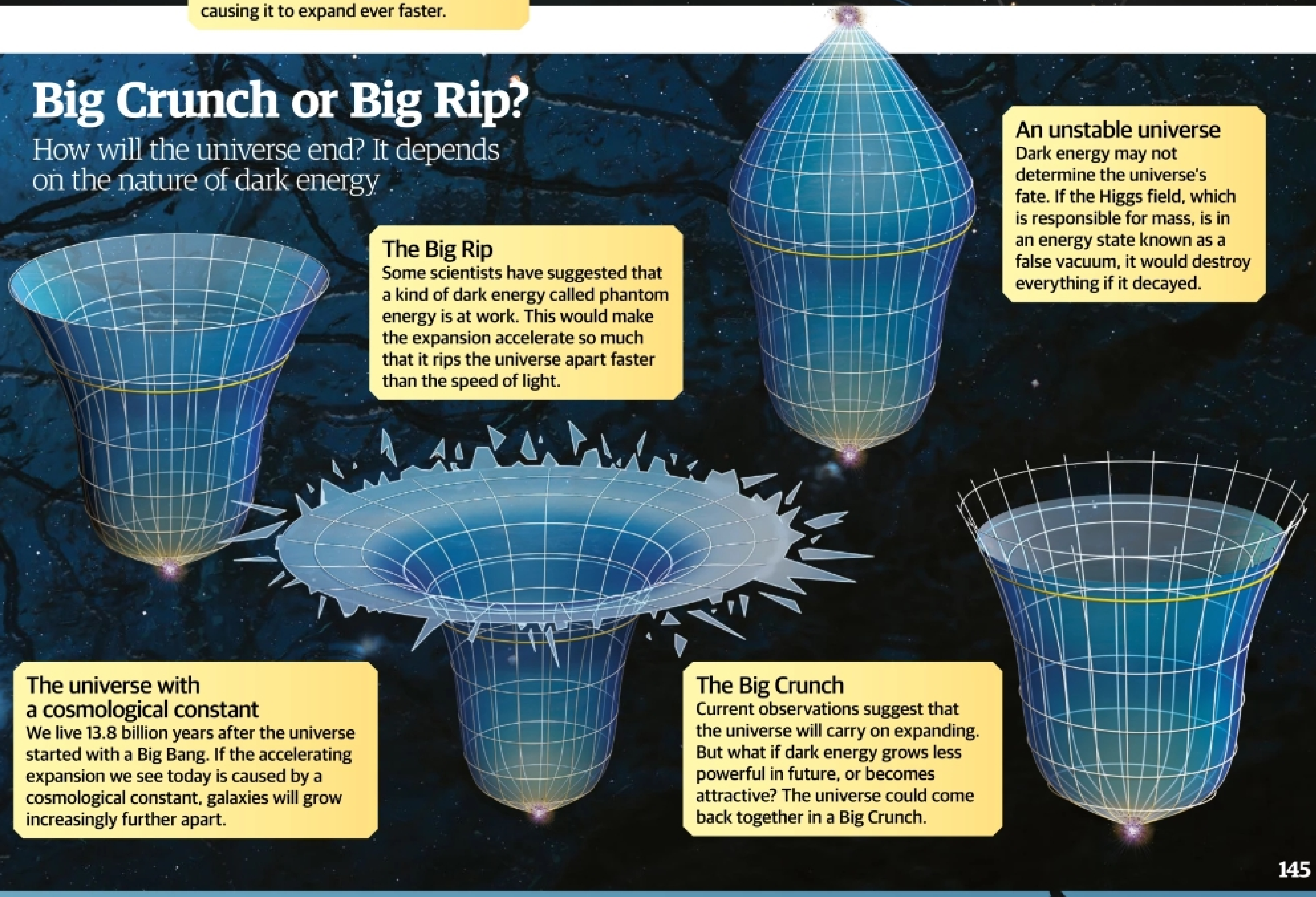
© NSF/LIGO ; Tobias Roetsch; Nicholas Forder

The universe today
Today astronomers observe the 'cosmic web' created by the influences of dark matter and dark energy. It consists of chains of galaxies strung together in filaments that stretch across the universe.

Dark energy takes over
About 5 billion years ago dark energy began to dominate. No longer was the gravitational attraction of matter and dark matter enough to slow the expansion. Dark energy had taken over, causing it to expand ever faster.

Big Crunch or Big Rip?

How will the universe end? It depends on the nature of dark energy



The Big Rip
Some scientists have suggested that a kind of dark energy called phantom energy is at work. This would make the expansion accelerate so much that it rips the universe apart faster than the speed of light.

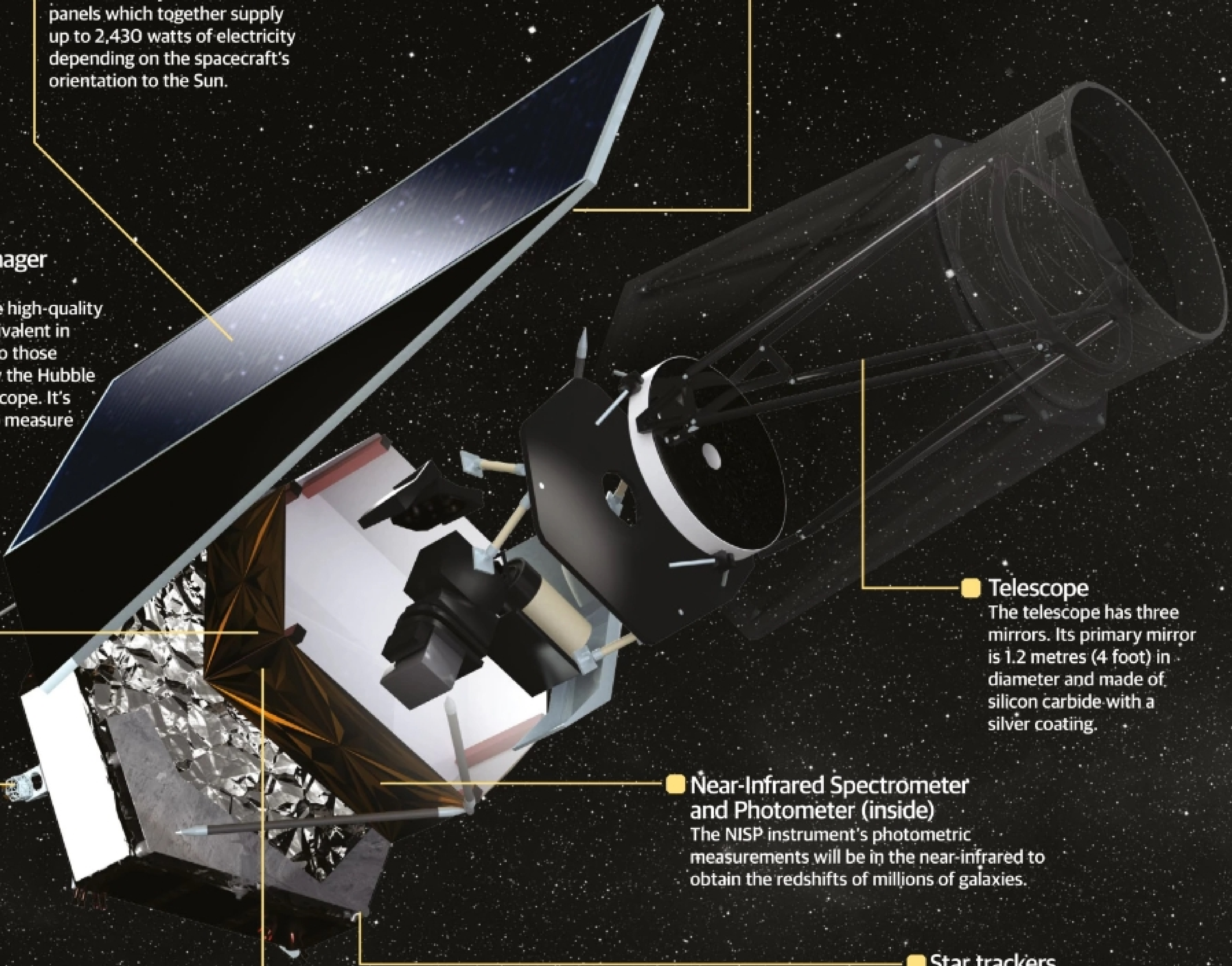
An unstable universe
Dark energy may not determine the universe's fate. If the Higgs field, which is responsible for mass, is in an energy state known as a false vacuum, it would destroy everything if it decayed.

The universe with a cosmological constant
We live 13.8 billion years after the universe started with a Big Bang. If the accelerating expansion we see today is caused by a cosmological constant, galaxies will grow increasingly further apart.

The Big Crunch
Current observations suggest that the universe will carry on expanding. But what if dark energy grows less powerful in future, or becomes attractive? The universe could come back together in a Big Crunch.

Euclid: mapping the dark universe

The spacecraft's instruments will observe billions of faint galaxies to reveal the signature of dark energy



Sunshield
The sunshield protects the payload module, which contains the instruments, from the Sun, and supports the solar panels on the other side.

Solar array
The solar array consists of three panels which together supply up to 2,430 watts of electricity depending on the spacecraft's orientation to the Sun.

Visible imager (inside)
VIS will take high-quality images equivalent in resolution to those captured by the Hubble Space Telescope. It's designed to measure the shapes of galaxies.

Telescope
The telescope has three mirrors. Its primary mirror is 1.2 metres (4 foot) in diameter and made of silicon carbide with a silver coating.

Near-Infrared Spectrometer and Photometer (inside)
The NISP instrument's photometric measurements will be in the near-infrared to obtain the redshifts of millions of galaxies.

Thrusters
The thrusters are powered by cold nitrogen gas so as not to disturb any measurements. This is supplied by four high-pressure tanks, holding a seven-year supply.

Dichroic plate (inside)
The dichroic plate splits incoming light, sending visible light to the VIS instrument and near-infrared light to NISP, allowing observations of both simultaneously.

Star trackers
Three star trackers measure the telescope's attitude (the direction it's pointing) by comparing what it sees to a built-in star catalogue.

How we can test dark energy

Measure galaxy shapes

Light is bent by matter, so galaxy shapes are distorted if there's a clump of dark matter between us and them. Mapping dark matter helps pin down dark energy's influence.

Detect supernovae

If a source of light moves away from us the wavelength stretches. This redshift shows how fast a Type Ia supernova is moving away from us, while its brightness reveals its distance.

Examine the CMB

The Cosmic Microwave Background (CMB) is radiation emitted just after the Big Bang. It's so far provided backing for a universe containing both dark matter and dark energy.

Look for new particles

If your lab equipment is sensitive enough you might be able to detect the minuscule effect of a 'fifth force' on atoms here on Earth. This small-scale experiment can be done in a short timescale.

© NASA; Gianluca Lombardi; Adrian Mann

Sunset over the Large Synoptic Survey Telescope, under construction in Cerro Pachón, Chile

a 3,200-megapixel camera – the world's largest. Currently under construction in Chile, its 8.4-metre (27.5-foot) diameter primary mirror will capture an image of the whole sky every three nights over a ten-year period.

And then there's the European Space Agency's Euclid telescope, which is expected to be launched into space in 2021. It will cover 15,000 square degrees of sky – that's ten-times the area of the Kilo-Degree Survey – observing a billion galaxies and peering 10 billion years into the past. The images it sends back to Earth will be spectacular – similar in resolution to those taken by the Hubble Space Telescope.

In preparation for the launch, Paniez Paykari is modelling Euclid to ensure the instrument performs as intended. A research associate at the Mullard Space Science Laboratory, she explains that while all measurements come with statistical uncertainty, Euclid will give cosmologists more precise data to work with. "In the past 20 years evidence from all probes has pointed to the existence of dark energy – that it's probably a cosmological constant but nothing more. If we can be exact with Euclid, we'll be able to tell if dark energy is constant or if it's dynamic."

What if the treasure trove of data from new observations, expected in the mid-2020s, sounds the death knell for the cosmological constant? One possibility could be that, despite passing every test thrown at it for decades, Einstein's general theory of relativity is wrong. Or at least that gravity may, in some circumstances, work differently than the theory describes.

> "If we can be exact with Euclid, we'll be able to tell if dark energy is constant or if it's dynamic" **Paniez Paykari**

"It might be gravity is not attractive on all scales. If you put two things close to each other they will attract because of gravity, but it may be that if you put them far enough apart they will repel. It could be that gravity is repulsive or somehow needs changing on cosmic scales," says Kitching.

Many modified-gravity theories have been cooked up by theoretical physicists, and only more data will determine whether or not they're correct. By a quirk of fate, many of these models were ruled out last year thanks to a gravitational wave signal named GW170817.

"It came out of the blue," says Kitching. "A merger of two neutron stars produced a gravitational wave signal and a flash of light at the same time. These arrived [at Earth] at the same time too, which means that light and gravitational waves travel at the same speed."

At a stroke, all the modified-gravity theories that also predicted different speeds for light and gravitational waves bit the dust. But there are plenty left, and it's likely to be quite some years before the dark energy riddle is solved once and for all.

The Abell 370 cluster consists of hundreds of galaxies held together by gravity

NASA SCIENTISTS

HAVE THEY MADE ALIEN DNA?

While scientists and sci-fi writers have pondered what alien life might look like, a group of researchers reckon it's what's inside that really counts

Reported by David Crookes

© Tobias Roetsch; Jesper Klausen / Science Photo Library

When NASA formed in 1958, it sought to expand human knowledge of space. The US agency looked to further science and technology, develop and improve aeronautical and space vehicles and send humans on an unprecedented voyage of discovery. It also sparked interest in the potential of life on other planets. Today detecting alien life is an important part of NASA's planetary science missions, and its chief Jim Bridenstine says it's a high priority. Next year NASA is once again targeting the Red Planet, sending the Mars 2020 rover skywards so that it will touch down and collect samples for eventual return to Earth.

Meanwhile, the European Space Agency (ESA) is sending its own rover to drill below the surface of Mars in the hope of finding life buried underground. And the fact that it will bear the name Rosalind Franklin is proving to be rather apt.

It was this British chemist and X-ray crystallographer who helped discover the structure of DNA - the building blocks of life - assisting in laying down the principles to which scientists have worked to ever since. There is a fundamental understanding of what DNA is and how it presents itself here on Earth. Only it would now seem that unimagined forms of life may also exist.

That's because scientists funded by NASA have developed a new type of molecular system that is able to store and transmit information just like DNA. It's entirely synthetic, and by no means a new life form, but it has stunning repercussions in the search for extraterrestrial life, not least because it presents a very real possibility that an alternative to DNA-based life may exist on other celestial bodies.

Far right (top): Astrobiologists have long been studying molecules and organic compounds in space to determine if life exists elsewhere in the universe

Far right: The top two base pairs show natural DNA, with the bottom two making up an additional synthetic pair as seen in hachimoji DNA

Below: Pictured in 1955, Rosalind Franklin also contributed to the study of coal, carbon and graphite

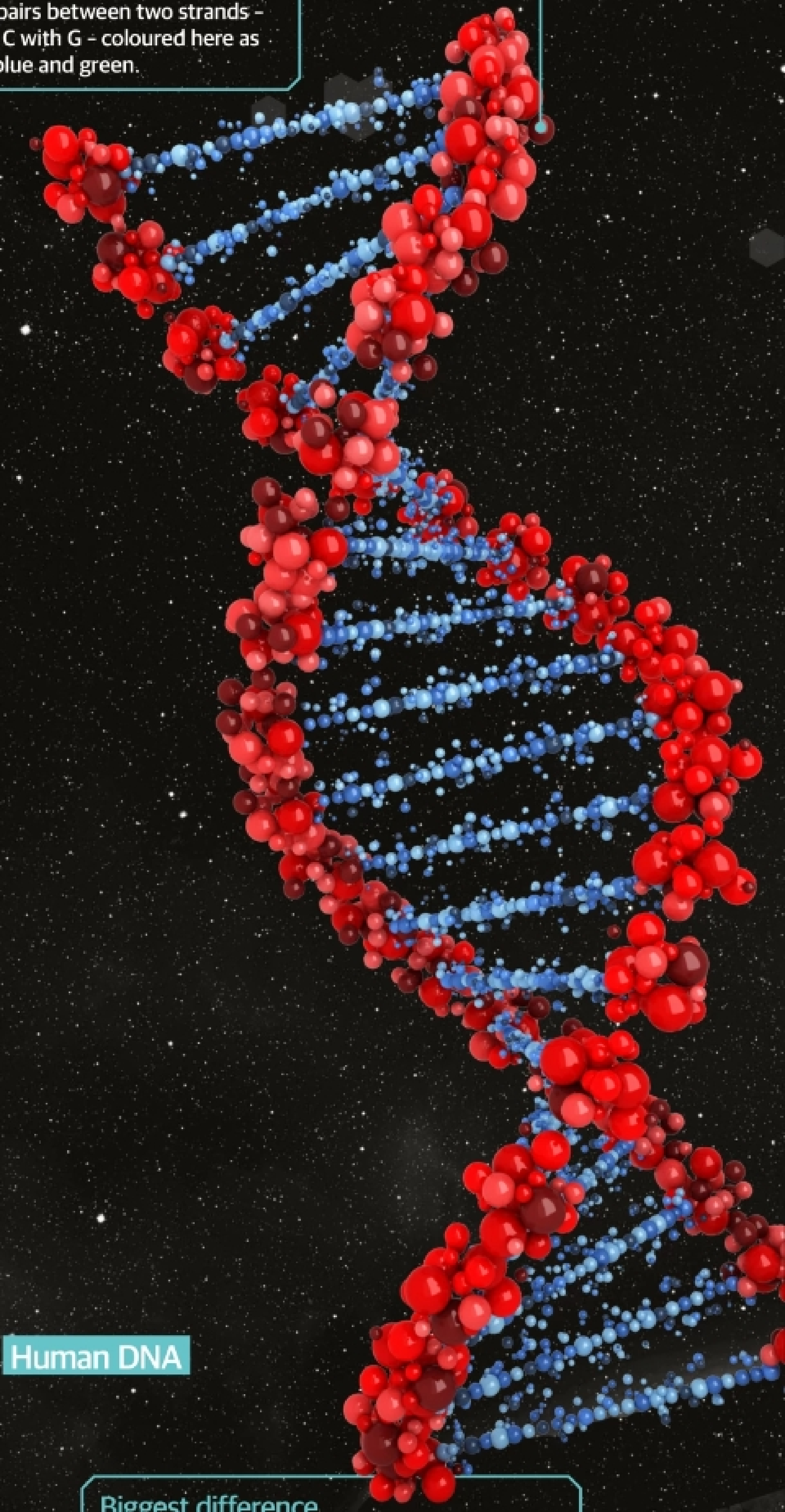
> "Scientists funded by NASA have developed a new type of molecular system that is able to store and transmit information"

Alien DNA vs Human DNA

How does the synthetic hachimoji DNA compare with the natural DNA found in your own body?

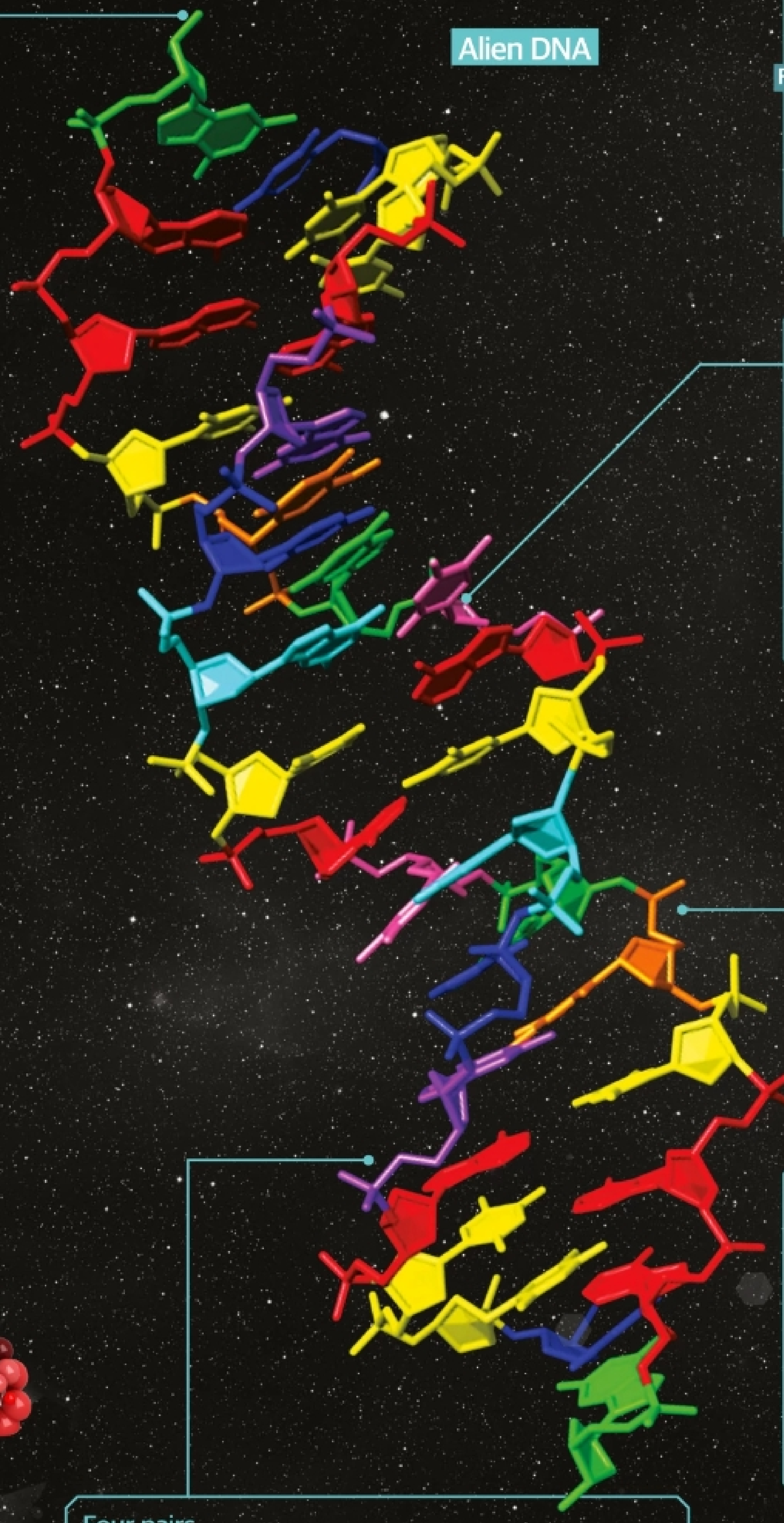
Regular DNA

Human DNA contains four building blocks, or chemical bases: adenine (A), cytosine (C), guanine (G) and thymine (T). These cross-link in pairs between two strands – A with T and C with G – coloured here as red, yellow, blue and green.



Biggest difference

Perhaps the largest difference is that human, or natural DNA, is known to exist in life forms, but the 'alien' DNA has not been found here or elsewhere. It simply points to the potential for eight informational ingredients rather than four.

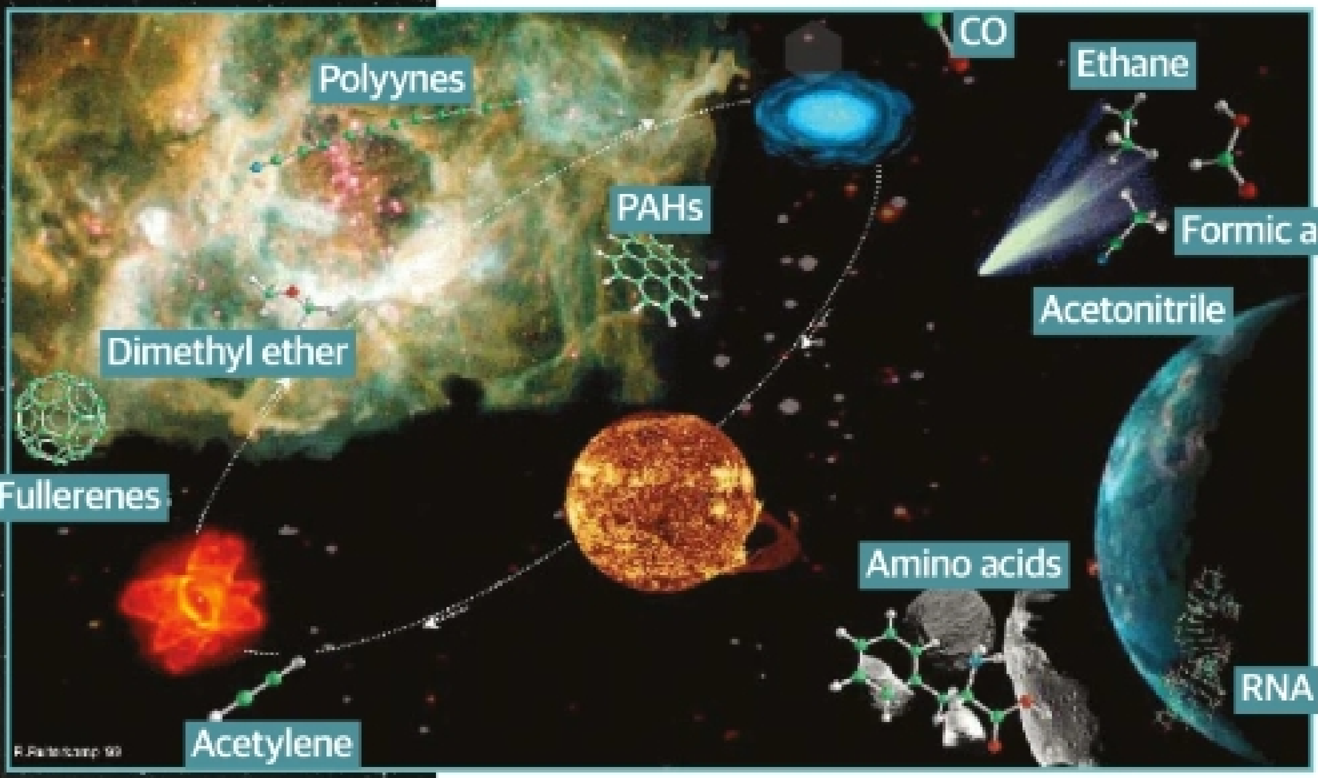


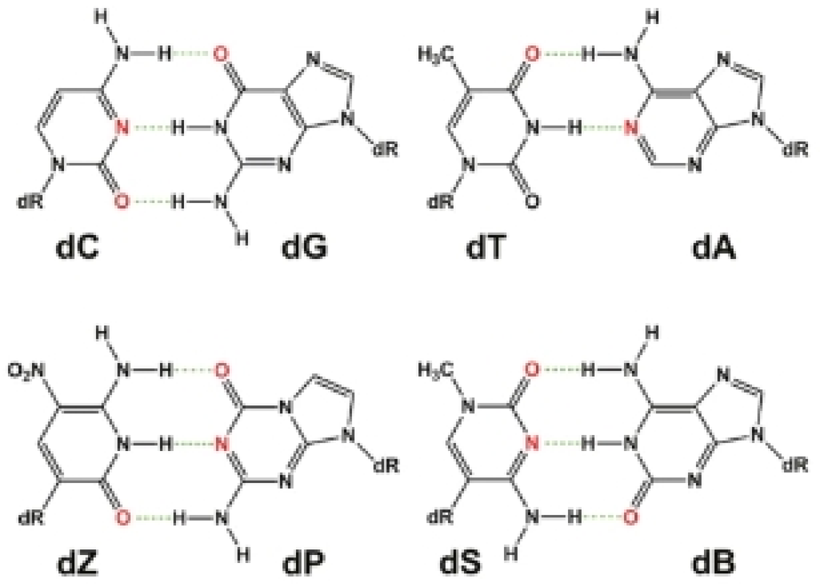
Double-stranded helix
Both the human and 'alien' DNA created by NASA-funded scientists have a double-stranded helix structure. The two strands of DNA are antiparallel – running in opposite directions – making them twist.

Alien DNA
Scientists have developed new synthetic bases that they have added to the natural DNA bases we know exist on Earth. In this image these additions are coloured pink, purple, cyan and orange.

New base pairs
Just as A only pairs with T and C only with G, forming hydrogen bonds in order to form two types of base pairs, so the synthetic nucleotide bases are explicitly linked. P binds with Z and B binds with S.

Four pairs
Whereas human DNA consists of two pairs of nucleotide building blocks, this 'alien' DNA – or hachimoji to give it it's proper name – has four. When tested with enzymes hachimoji DNA strands translate into hachimoji RNA, allowing instructions to be carried to make proteins – just like natural DNA.





In that sense the breakthrough allows scientists to reconsider just what they could be looking for when they search for extraterrestrial life. But just what have the scientists done, and why is this important? To answer those questions it is crucial to understand the long-established fundamentals of DNA and how this new molecular system expands our ability to programme genetic systems into a new realm.

DNA – or deoxyribonucleic acid – was first isolated in 1869 by Swiss physician Friedrich Miescher, and it led to many decades of work. Scientists would establish DNA as a complex molecule existing in the nucleus of every cell, storing and transmitting genetic information, and they would discover that it consists of a deoxyribose sugar, phosphate and base. The base would be either adenine, thymine, guanine or cytosine – four important ingredients knows as nucleotides – and these were given the letters A, T, G and C.

In mid-March 1953, James D. Watson and Francis H. Crick worked out DNA's molecular model based on an X-ray diffraction image taken by Franklin, figuring that it was made up of two long molecules arranged in a spiral. The twisting strands of DNA were seen to combine into what is known as a double-helix structure, held together by complementary base pairs which always hook up in a certain manner. Thymine, for example, always pairs with adenine, and guanine always pairs with cytosine: T to A and G to C. Crick announced that the secret of life had been discovered.

Yet in February 2019, NASA previewed the results of further groundbreaking research that was to appear in *Science* magazine. It reported that a team

© ESA; MRC Laboratory of Molecular Biology; Leigh Prather / Alamy Stock Photo; Indiana University School of Medicine

> "The results constitute an important breakthrough in the efforts to someday redesign life as we know it" **Dr Eugene Wu**

led by Steven Benner at the Foundation for Applied Molecular Evolution in Alachua, Florida, had fabricated a new informational molecular structure - that is, something which functions like DNA and allows information to be stored and transmitted. The big difference is that this did not make use of four ingredients. Instead, it used eight.

"The Benner team took the existing four letters of DNA (A, T, G, and C) and four letters of RNA (A, U, G, and C) and made some chemical tweaks to form new letters that have approximately the same shapes and sizes as the existing letters," explains Dr Eugene Wu, associate professor of biology and biochemistry at Richmond School of Arts and Sciences.

Indeed, by adding four synthetic nucleotides identified as P, B, Z and S to the four present in DNA and RNA - the latter being ribonucleic acid, a large molecule which carries out the instructions encoded in DNA - the scientists successfully created four allowed base pairs rather than two. In other words, they could add two unnatural base pairs to the T to A and G to C arrangement of DNA that would mimic the structures of the ingredients in regular DNA and function in the same way. The result is a new double-helix structure that has a much greater capacity to store information.

"It was a matter of taking the existing base pair shapes and hydrogen bonding patterns from the Watson-Crick base pairs and changing the hydrogen bonding partners without substantially altering the shape," explains Wu, who was not involved in the research. "They designed the four new bases in such a way that they only pair with their intended partners, and not with other bases. Then it's just a matter of chemical synthesis and using existing DNA synthesisers to put the new letters into chains."

Benner's research project began 30 years ago, with the challenge being to reproduce the properties we value in living systems but on a molecular platform different to what prebiotic chemistry on Earth has delivered.

The research had two conceptual aims. First, it wanted to determine if alien life would use the same core molecules as life on Earth to support reproduction, evolution and adaptation, given it would have had an independent origin and different natural history. Second, it sought to synthesise an alternative genetic system to see if it was really possible. This proved to be successful.

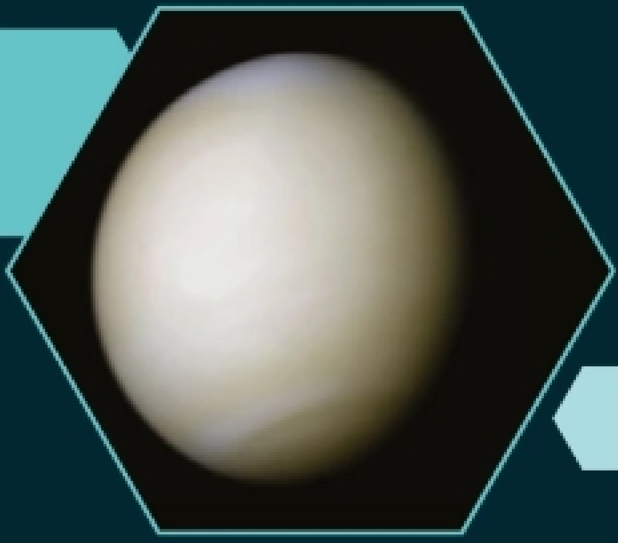
As such, the team has given their creation a name, dubbing it hachimoji - 'hachi' means 'eight' and 'moji' means 'letter'. It is the first time that eight letters have been used in a DNA-like structure, with earlier attempts topping out at six. Importantly, the researchers developed a system that was stable, predictable and programmable. They can predict how it will behave at different temperatures and figure a set of rules.

"The discovery of four new bases for genetic informational storage is really quite clever," says Wu. "If you could imagine Watson and Crick working out the rules for making base pairs in DNA in 1953, this would be like taking those same rules and just moving the hydrogen bonding partners around.

"It immediately begs the questions, could life contain an alphabet of more than four letters and, if so, why did we end up with A, T, G, and C? In addition the research results constitute an important breakthrough in the efforts to someday redesign life as we know it."

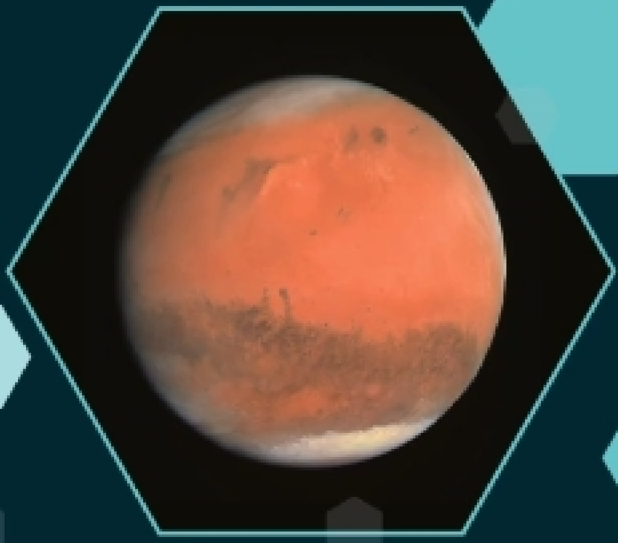
As it stands, Benner tells us that the system created in the lab has four of the five features valued in a biopolymer that can support life. "It stores information in a rule-based, predictable

Where are we likely to find life?



Venus

Venus is dry and incredibly hot, making it a very inhospitable planet, but some scientists suggest it would have been habitable more than 2 billion years ago when it was far more temperate. There's even a suggestion life retreated to the planet's cooler clouds - which are mostly sulphuric acid - and that life could remain there today!

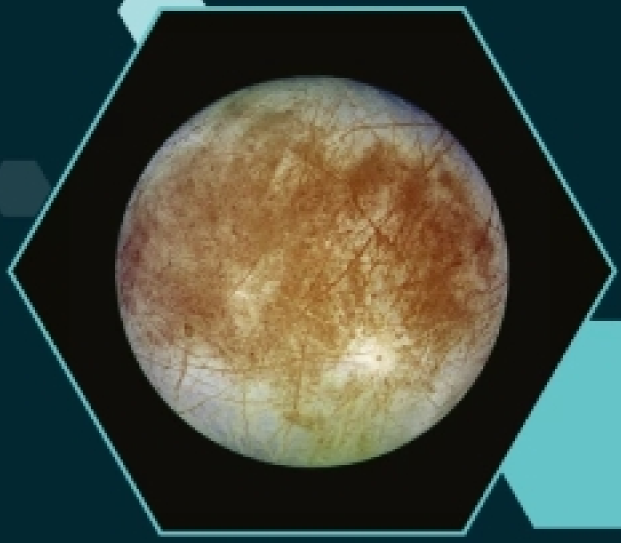


Mars

It's a long-held dream that the Red Planet harbours life - David Bowie even sang about it. Although it's yet to be found, there's still great optimism. The past existence of liquid water - still found as low-volume liquid brine - gives hope. Scientists have also detected methane, suggesting an active surface.

Ceres

Ceres is a dwarf planet which lies between the orbits of Mars and Jupiter, and scientists are keen to discover if it has the potential for life. They're particularly excited because Ceres has water. NASA also found that it is rich in organic matter and contains crucial chemicals such as ammonium.

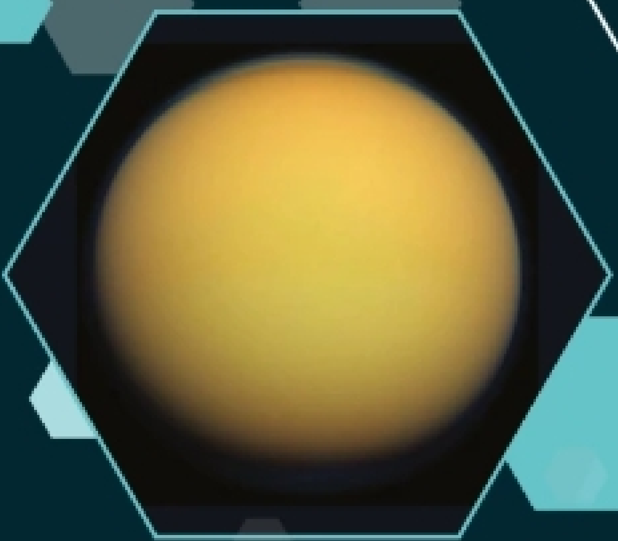


Europa

The icy world of Europa orbits Jupiter, and while it may be a fraction smaller than Earth's Moon, it has huge potential for life. There is an abundance of liquid water beneath the surface and, in 2013, NASA detected 'clay-like minerals' on the moon's surface. These are associated with organic matter on Earth.

Enceladus

Not only does this moon of Saturn have a global salty ocean beneath its icy crust that is likely being heated by thermal effects, the Cassini-Huygens probe in 2005 detected carbon, nitrogen, oxygen and hydrogen. There are also large geysers of water vapour at the south pole, all of which are rather exciting.



Titan

Another one of Saturn's moons – and the largest of the 62 – Titan has a thick, chemically active atmosphere which is rich in carbon compounds. It's therefore one of the most Earth-like of worlds and, since it has stable liquids on its surface and a hydrological cycle, the chance of life is one scientists are keen to explore.

Above: NASA's statement on the hachimoji breakthrough questions whether moons such as Europa may contain life which doesn't use our DNA

Far left: A NASA researcher performs DNA and RNA sequencing on microbes, but have we been too focused on looking for what we know exists?

fashion, and we show it gives predictable double helices with thermodynamic rules as good as with four-letter DNA," he says. "That information can be transferred to other biological molecules. Here, we found enzymes that allow the synthesis of eight-letter RNA by transcription of eight-letter DNA."

He goes on to say that, both directly and as transferred, the information can confer a selectable phenotype: "Here, the selectable phenotype was green fluorescence." He adds that "the information can evolve. This was shown by multiple crystal structures. Biochemists in the laboratory can set up in-vitro selection systems that will force hachimoji DNA and hachimoji RNA to evolve to have many selectable phenotypes.

"As an example, we have evolved pieces of hachimoji DNA to bind to breast cancer cells, liver cancer cells and anthrax toxin. We are now evolving pieces of hachimoji DNA that are adapted to selectively cut proteins that are responsible for disease."

Scientists can certainly start to think about the implications of elegantly increasing the number of DNA building blocks from four to eight. "It dramatically expands the information density of nucleic acids," says Professor Michael Jewett of Northwestern University. "The fact that the high-resolution crystal structures for this new eight-letter hachimoji DNA code are similar to the normal four-

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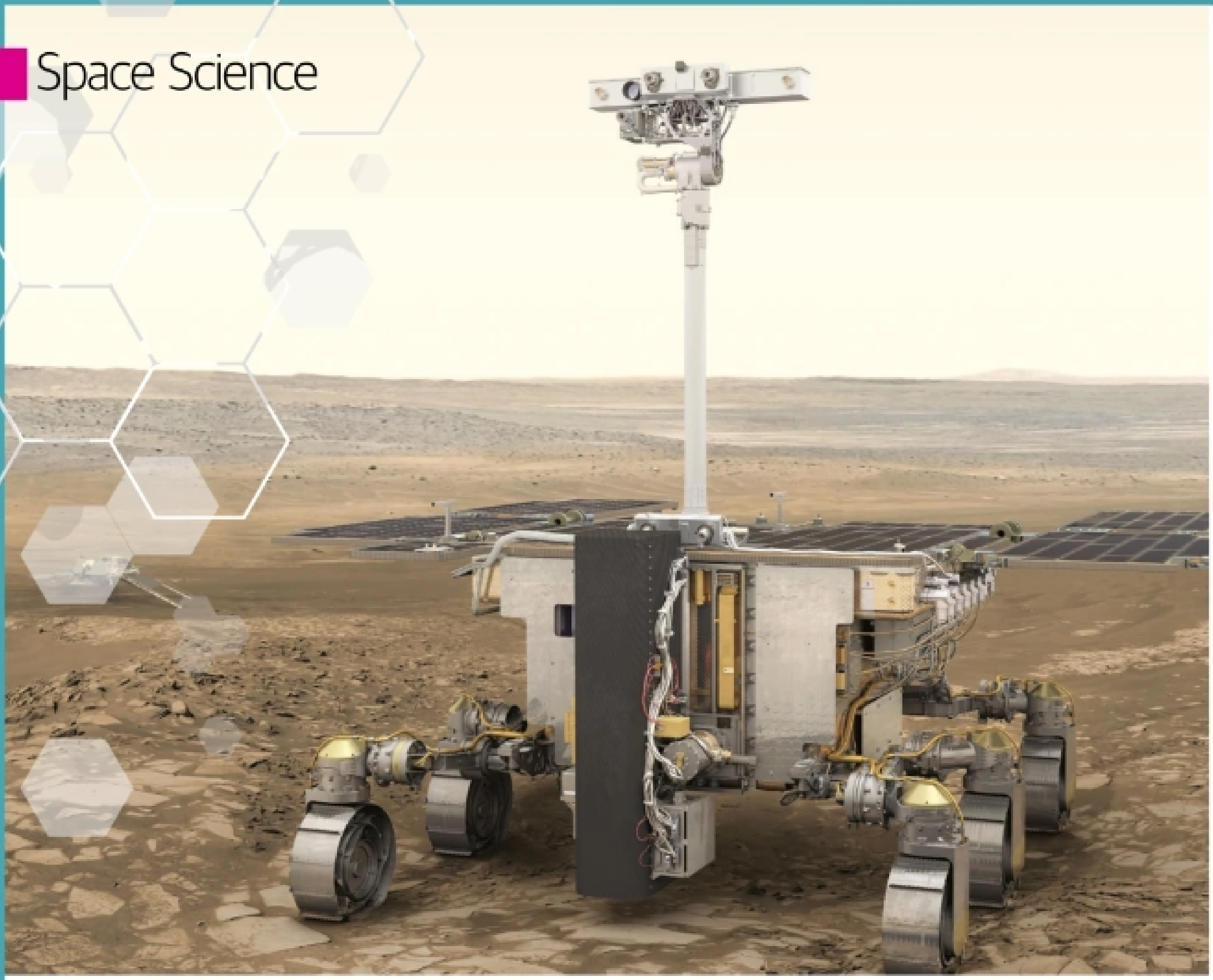

> "The approach described here could help bypass the limitations of natural translational biochemistry" **Professor Michael Jewett**

What could this mean for the future of hunting for life?

"It is inadequate to simply speculate about what alien life might look like. It is necessary to go into the laboratory with specific, actionable chemical structures and see how they perform"
Steven Benner, distinguished fellow at the Foundation for Applied Molecular Evolution

"This new work will help us to develop effective instruments and experiments that will expand the scope of what we look for"
Lori Glaze, acting director of NASA's Planetary Science Division

"Incorporating a broader understanding of what is possible in our instrument design and mission concepts will result in a more inclusive and therefore more effective search for life beyond Earth"
Mary Voytek, senior scientist for astrobiology at NASA headquarters

"The discovery that DNA with eight nucleotide letters is suitable for storing and transmitting information is a breakthrough in our knowledge of the range of possibilities necessary for life"
Andrew Serazin, president of Templeton World Charity Foundation

Above left: ESA's ExoMars rover has been named after Rosalind Franklin, whose work was crucial for the understanding of DNA

Top: Many asteroids and comets have smashed into planets – could they have delivered the key ingredients of life?

Above: An image showing organic material on Mars that could be a biomarker sign of past life

Right: Phosphorus – a key component of DNA and cell membranes – was discovered on the Rosetta comet

letter code used in human DNA additionally makes possible many transformative applications, from digital DNA storage to molecular evolution.

"For example, efforts to repurpose ribosomes to expand the range of genetically encoded chemistry rely on expanding these codons that could be reprogrammed. In principle a hachimoji system could extend the codon space in full life forms from 64 to 512. Thus, the approach described here, if it could be used in living systems, could help bypass the limitations of natural translational biochemistry for new biocontainment and manufacturing applications."

Hachimoji also impacts the ongoing search for life, with Benner suggesting the work "expands our understanding of the types of molecules that might store information in extraterrestrial life on alien worlds".

"More specifically, as NASA designs missions to search for alien life in the cosmos, should it be looking for DNA as if DNA is the only biopolymer that can support Darwinism? Or can many biopolymers support Darwinism, requiring NASA missions to construct their search strategies more broadly?" he queries.

Indeed, according to NASA it raises many questions about the nature and structure of life elsewhere. Inhospitable environments that would prevent life as we know it on Earth from flourishing could see an abundance of different types of life forms since it points to there being a potential for alternative genetic systems. Scientists need to be alert to the possibility that other worlds do use our DNA, and they need to work out ways of being able to recognise it. Researchers also suggest that hachimoji DNA could develop clean diagnostics for

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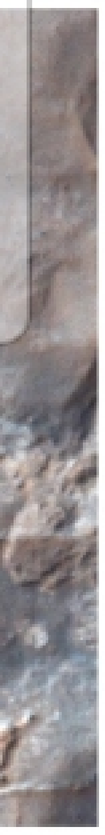


human diseases and open the way for DNA digital data storage. But could it even be used to create full life forms?

"The idea of creating a new life form that lives by a different code comes immediately to mind," says Wu. "With eight letters instead of four, a three-letter codon could code for 8x8x8, or 512 different possible combinations. Even a two-letter codon could code for 8x8, or 64 different combinations, same as the existing biological genetic code.

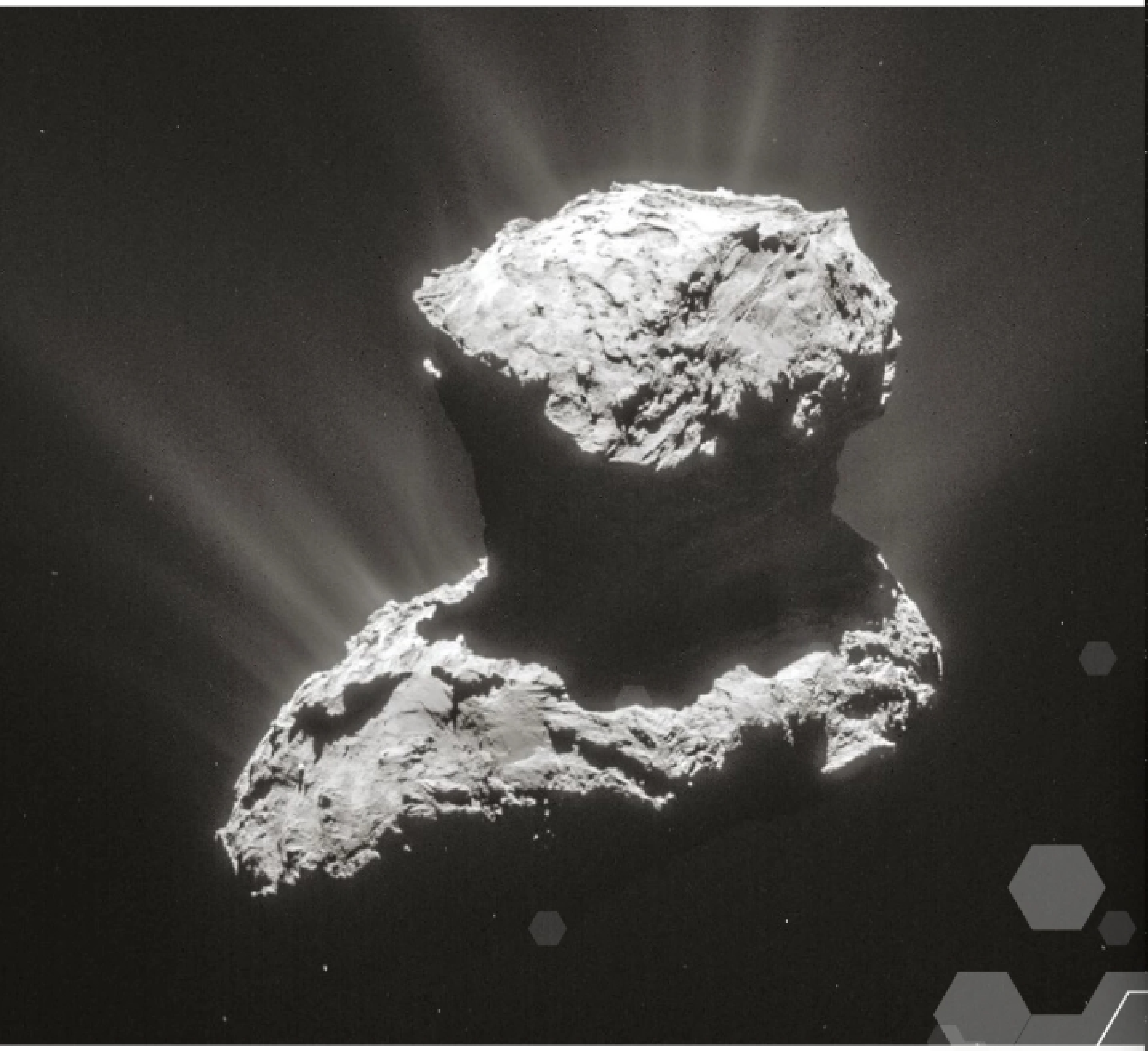
"But a cell containing a two-codon, eight-letter code would be completely incompatible with existing life, even if every single protein were the same. The first thing that could be done would be to incorporate an unnatural amino acid into proteins by matching it with a three-letter codon that uses hachimoji RNA. Even that is a challenging biochemical engineering project, but certainly conceivable."

So far Benner and his team have developed synthetic enzymes that copy hachimoji DNA into hachimoji RNA, allowing the transfer of stored information so that instructions can be carried out within an organism. They haven't, however, sought to take things further by actually creating something that could be self-sustaining – and although fears have been expressed that the synthetic DNA could leak from the laboratory and cause an alarming biohazard, the system actually needs a steady supply of unique building blocks and proteins that are only found in the lab. "It must be nurtured constantly by attentive scientists," Benner says.

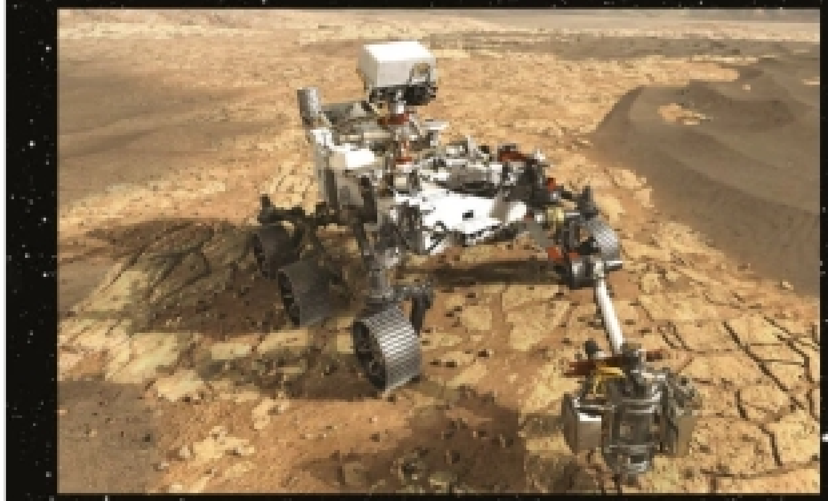
In any case, the researchers are also not claiming that this exact system exists in the universe, and it is ultimately an exercise in showing what is possible: the beginning of a larger journey and something of an awareness campaign. But what could DNA actually be like on other worlds? "That," says Wu, "is a much bigger question."

"We can say that alien life might have eight-letter DNA on other worlds," adds Benner. Certainly, if the fundamental idea of evolution holds true for other worlds, a genetic system would have to at least be able to store, transmit, express and change information.

"The simplest way to do this would be through polymers of molecules with a backbone where the connections between building blocks are made," he says. "One could imagine a simpler system with only two letters in the genetic alphabet. Also, if other worlds have little or no accessible phosphorus, their informational molecules would be very different than DNA and RNA. It's even possible that the informational molecule on another world might be branched or three dimensional, not just a linear polymer. Hard to imagine when we've only got the one way that worked here."



Missions on the hunt for alien life



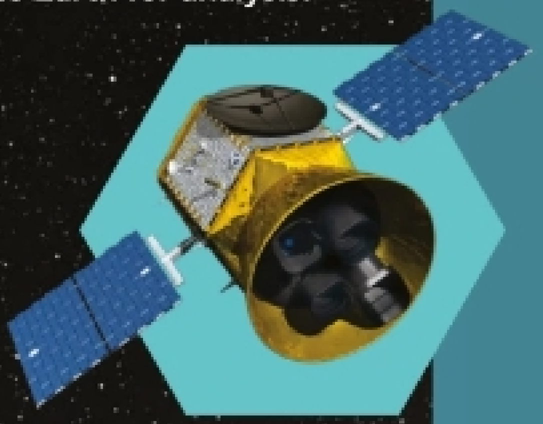
Mars 2020

Mission aims

To seek signs of past habitable conditions on Mars and search for signs of microbial life.

This rover by NASA's Mars Exploration Program is set to launch next summer and begin investigations in 2021. It will collect dozens of samples of surface soil and rock cores which will eventually be sent back to Earth for analysis.

Transiting Exoplanet Survey Satellite

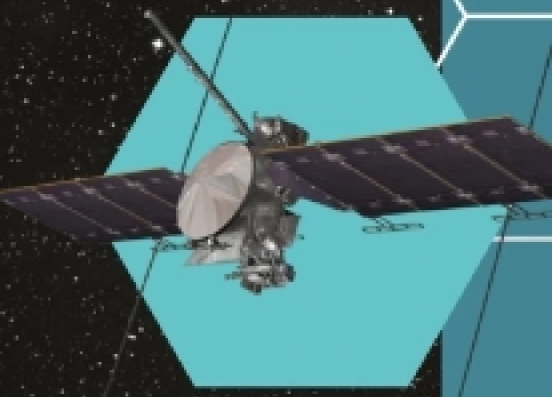


Mission aims

To find planets outside of our Solar System, including those that may support life.

TESS launched on 18 April 2018 to search for exoplanets around nearby stars. A catalogue has since been created noting potentially habitable planets; the idea is that it helps researchers find the most promising candidates.

Europa Clipper



Mission aims

To conduct a reconnaissance of Jupiter's moon Europa to check for signs it could harbour life.

Due to launch in June 2023, the craft will orbit Jupiter and study Europa in light of the Galileo probe having noted a subsurface ocean. Radar will determine the thickness and composition of its icy shell.

OSIRIS-Rex

Mission aims

To sample 60 grams of the asteroid 101955 Bennu and return it to Earth for analysis.

Although scientists have been keen to study Bennu to understand more about how the Solar System has formed and evolved, the mission has discovered signs of water. It will likely offer clues about the origins of life on Earth.

Think you understand gravity? Think again. The everyday force is a constant source of questions for physicists - and some are looking to replace the theory

Reported by Abigail Beall

GRAVITY

WHY DOESN'T IT MAKE SENSE?

© Tobias Roetsch

Gravity is everywhere, and you can see the effects everywhere you look. It's the reason the planet orbits around the Sun, the Moon orbits Earth and your feet stay planted firmly on the ground. It's one of the first aspects of physics we encounter at school, for example, with the tale of Newton and his apple falling off his head. Yet we know surprisingly little about this 'invisible force'.

Gravity belongs to a family of four forces that between them can answer pretty much any question along the lines of 'why does that happen?' when it comes to physics. Along with the strong force, the weak force and the electromagnetic force, the gravitational force governs the way everything interacts with each other in the known universe.

Gravity has been a source of wonder for humans since 1687 when Newton realised a force was needed to 'keep the Moon in her Orb'. Because of this long history, it would be understandable to assume gravity is the most well-understood of the forces, but it's not that simple.

Some of the greatest scientists to have lived, notably including Einstein, have dedicated their lives to understanding the force of gravity. Newton described gravity as a force, but Einstein went further, showing gravity to be the result of how mass and energy distort space and time. As a result, we are clued up on how it works on a classical scale in moderate gravitational fields - think of how satellites orbit the Earth, or how planets orbit the Sun, all of which can be described by Newton's equations of motion.

The exception was Mercury's orbit around the Sun, which Newton could not explain. Mercury, being so close to our nearest star, experiences a stronger gravitational field and it took Einstein and his General Theory of Relativity in 1915 to explain how that stronger gravity influences the swift world's path.

What is more, Einstein's theories predict how massive objects like stars distort space-time to the extent that they bend light around them, magnifying it in a process known as gravitational lensing. Predictions Einstein made in equations almost 100 years ago are still being tested in the most extreme gravitational environments that we know of, such as around black holes and binary neutron stars, and those equations are turning out to hold true now. For example, the first evidence showing how the motions of stars orbiting a supermassive black hole are affected in accordance with general relativity was published in August of last year.

But there are a few key problems with gravity that still need to be explained.

"There are many mysteries about gravity" says Paul Sutter, astronomer at Ohio State University.

What causes gravity?

"We think it may be caused by a particle called a graviton. Gravity is the ultimate force of attraction throughout the universe. Everything with mass also has gravity, including stars, planets and even people. The pull of an object's gravity gets stronger as you get closer, and its strength is proportional to the object's mass. Something as big as the Earth has enough gravity to keep us pulled down to its surface, and the Sun has enough gravity to keep the Earth orbiting around it. The mathematics of gravity were first described by Isaac Newton in the 17th century, while Albert Einstein, about 100 years ago, showed how gravitation could be better understood as a warping of space and time."

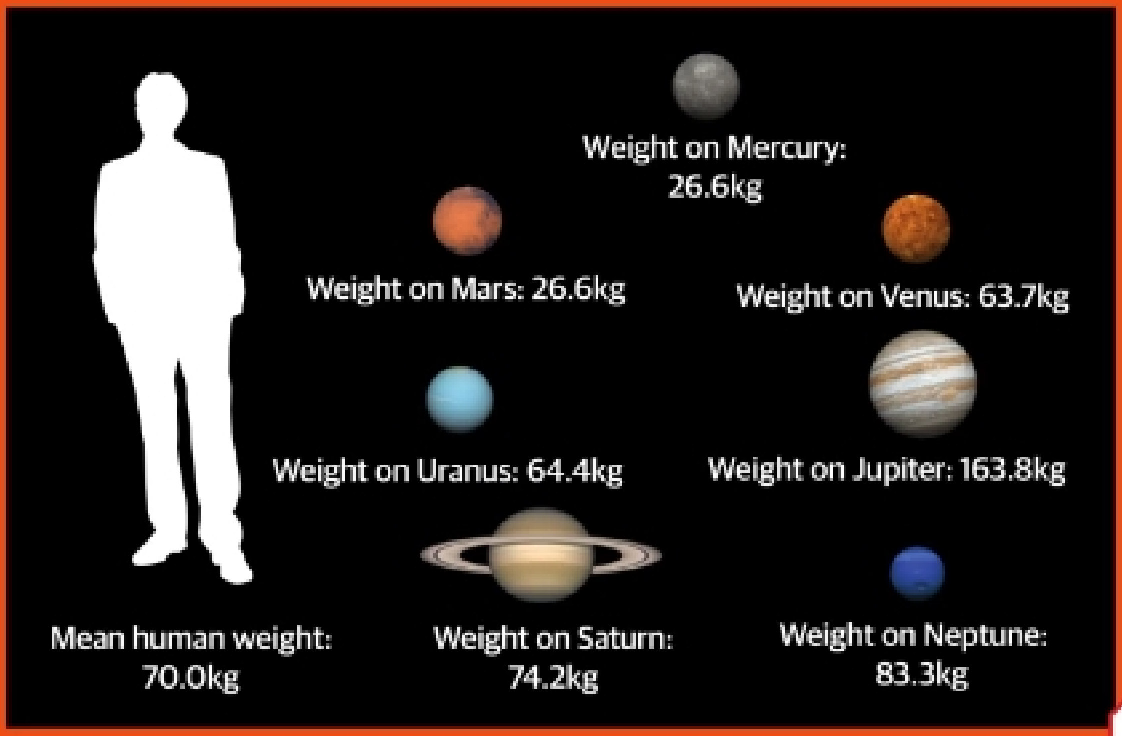
Dr Robert Hurt, NASA Spitzer Space Center

What exactly is gravity?

It has a lot of effects that we may not even think about

1. It gives us weight

Although your mass – the amount of 'stuff' that you are made of – would remain the same wherever you are in the universe, your weight would vary considerably. Weight is a force determined by gravitational attraction. It's the product of a large body's 'acceleration due to gravity' (g) and its mass. So, for example, if your mass – not weight – was 70kg and Earth's g is 9.81m/s^2, your weight would be 686.7 Newtons.

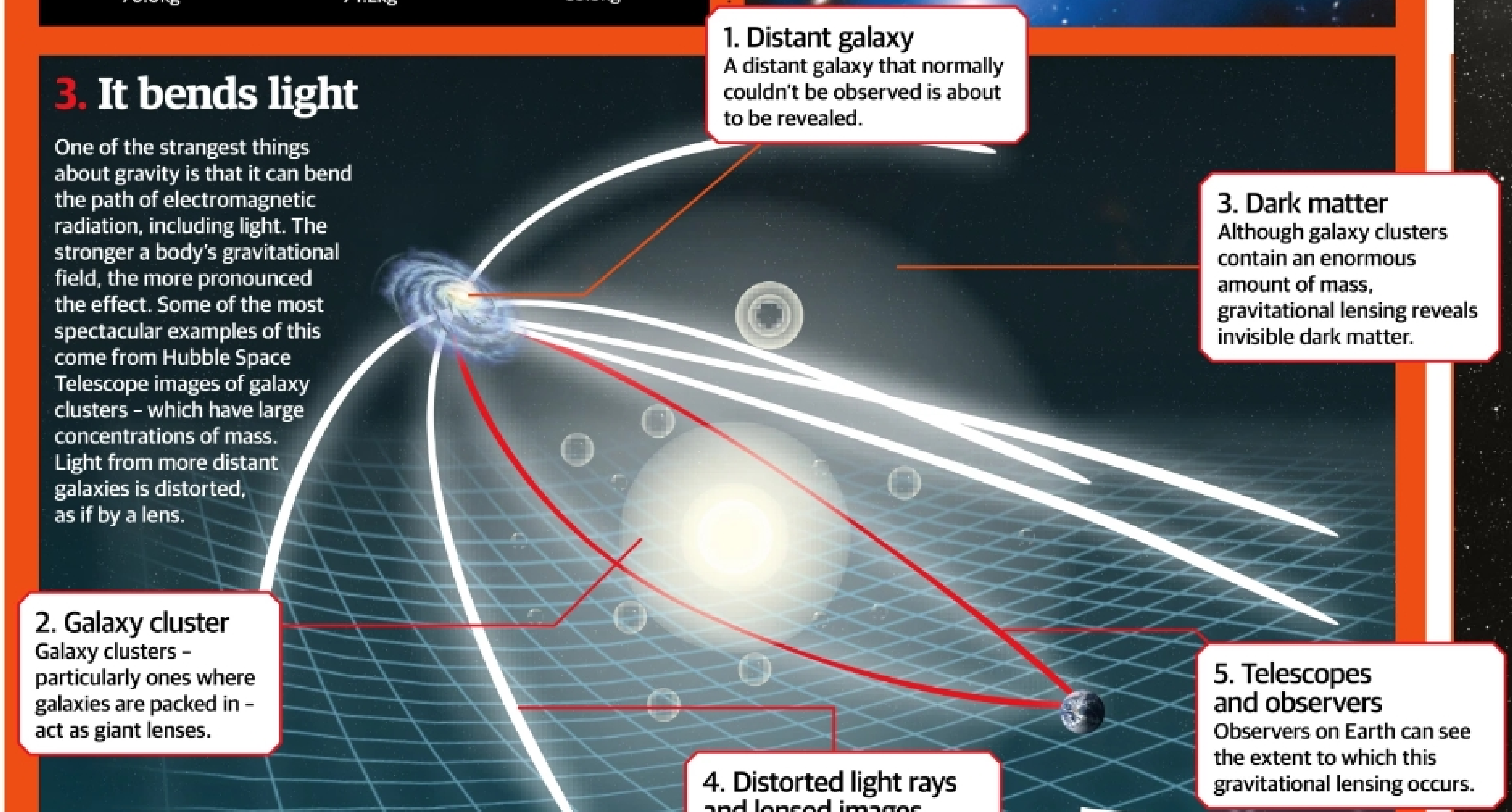

Weight on Mercury: 26.6kg
Weight on Mars: 26.6kg
Weight on Venus: 63.7kg
Weight on Uranus: 64.4kg
Weight on Jupiter: 163.8kg
Mean human weight: 70.0kg
Weight on Saturn: 74.2kg
Weight on Neptune: 83.3kg

2. It causes objects to gravitate towards each other

Bodies with significant mass can influence one another across thousands of astronomical units, or AU (one AU being the distance between Earth and the Sun). It's no surprise that planets close to the Sun should orbit it in a gravitational 'dance'. What is surprising is that so should a tiny dwarf planet like Sedna, which gets out to 936 AU.

3. It bends light

One of the strangest things about gravity is that it can bend the path of electromagnetic radiation, including light. The stronger a body's gravitational field, the more pronounced the effect. Some of the most spectacular examples of this come from Hubble Space Telescope images of galaxy clusters – which have large concentrations of mass. Light from more distant galaxies is distorted, as if by a lens.



1. Distant galaxy
A distant galaxy that normally couldn't be observed is about to be revealed.

2. Galaxy cluster
Galaxy clusters – particularly ones where galaxies are packed in – act as giant lenses.

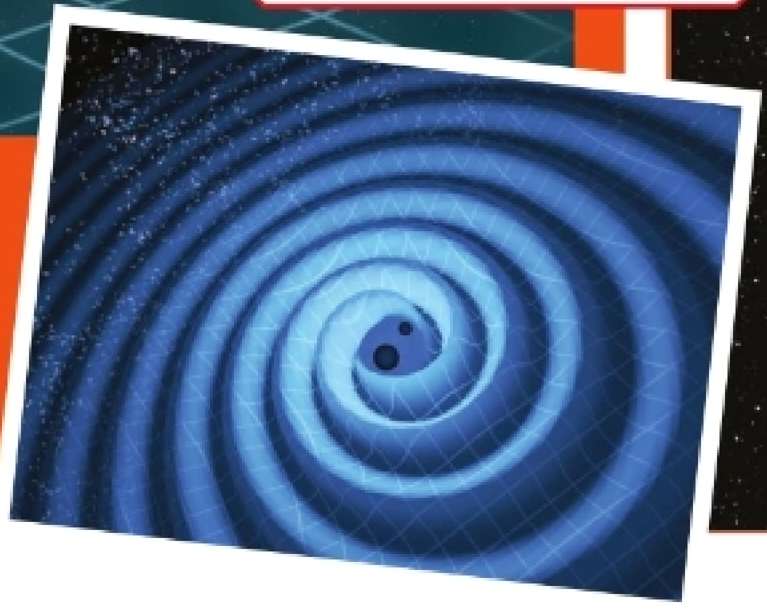
3. Dark matter
Although galaxy clusters contain an enormous amount of mass, gravitational lensing reveals invisible dark matter.

4. Distorted light rays and lensed images
Light rays from the galaxy are distorted and lensed by the cluster's gravitational field.

5. Telescopes and observers
Observers on Earth can see the extent to which this gravitational lensing occurs.

4. It causes ripples in space-time

One of the most extraordinary discoveries of this century was the existence of gravitational waves, or 'ripples' in space-time. These were detected by the Laser Interferometer Gravitational Wave Observatory, operated by Caltech and MIT, in September 2015 and are thought to have come from two colliding black holes 1.3 billion light years away. Although it was thought that gravitational waves could be detected from such an extreme event, no one had any idea when, or if, that would happen.



"For one, why is it so weak? It's far, far weaker than any of the other forces."

Gravity might not feel feeble when you are walking up a steep hill, or falling over. Yet the fact that you can overcome the force of gravity from a mass as large as the Earth's and stand up straight highlights how weak it is, comparatively. Gravity is around 1040 times weaker than the other forces, including the electromagnetic force that holds atoms together. It's even weaker than the 'weak force' that causes radioactive decay. Maybe gravity has been given the wrong name.

There are a multitude of theories as to why gravity is so weak, but no clear leading contender. "I don't think any current options look very promising right now," says Sutter. "We're floundering when it comes to extending our knowledge of physics, and we're only now beginning to design what we hope to be the right kinds of experiments to give us a clue as to what nature is thinking."

However, the answer could lie in solving the problem that not only eluded Einstein, but every physicist since – the unification of gravity, which describes things on very larger scales, with quantum physics, which is famous for describing behaviour on very tiny scales.

If gravity is quantised on the smallest scales, like light is, then it must have a particle that carries its force through quantum fields. For light, this particle is the photon. Gravity's force carrier would be the graviton, but it remains merely hypothetical at this point in time.

Two of the most popular attempts to derive a quantum theory of gravity are String Theory and Loop Quantum Gravity. String Theory proposes that all of matter is made up of tiny vibrating strings, and that one of these vibrational states represents that of a graviton. String Theory also requires extra dimensions beyond the four of space and time that we are familiar with, and some scenarios suggest that the gravity we experience is weak because it is leaking in to our four-dimensional space-time from another dimension that is curled up so tight that we can't otherwise detect it.

Meanwhile, Loop Quantum Gravity tackles the problem from a different angle by saying that space itself is quantised - that is, it can be broken down into the smallest possible pieces called quantum loops of gravity. However, it's still a fairly undeveloped theory, since it does not predict the graviton and it hasn't been shown that it is related to general relativity.

Like electromagnetism, gravity has an infinite range, which means it only gets weaker and weaker the further the two objects are apart, and never goes completely to zero. This is unlike the weak and strong forces, which only work within a specific range. This itself is not a problem when it comes to understanding gravity, but it does make gravity a strong driver of the universe around us.

Gravity is an attractive force only, and because of this it cannot be cancelled out. This

> "Einstein threw a spanner in the works when he described gravity as not a force, but a consequence of the structure of space-time"

Where can we find gravity?

From the phone in your hand to the stars in the sky, gravity is everywhere

Standing on Earth

The reason you do not float up into space is because of the force of gravity between the planet and your body.

Being used by your phone

Your phone has a tiny device called an accelerometer that uses gravity to work out which way the phone is orientated.

In distant galaxies

Every galaxy in the universe is bound together by the force of gravity, caused by the attraction of all its stars and planets.

In the Solar System

Each planet that orbits our Sun is driven by the force of gravity attracting it to our own personal star.

Gravitational lensing has been used to map the distribution of mass around stars, galaxies and clusters of galaxies

© NASA/ESA; LIGO

Gravity is crucial for life on Earth; without it we would not even have a planet

makes it very different to electromagnetism, which can attract and repel. The fact it is only attractive means gravity permeates across the vast distances in the universe with nothing getting in the way. But this is also another reason it makes no sense, according to some scientists.

Martin Tajmar, Professor of Physics at the Technical University Dresden, in Germany, says the strangest thing about gravity is "that there is only positive mass around us with no negative counterpart as in electromagnetism".

If an electromagnetic force is attracting an object, applying an opposite force would balance the original out, meaning the net force on the object would be zero. In what would potentially be the equivalent of this phenomenon but for gravity, Tajmar is looking into ways to 'counter' gravity, an 'anti-gravity' of sorts. He hopes come up with an opposite kind of force that would balance the gravitational pull of an object.

The idea of countering gravity is not only important for making gravity behave like all the other forces. It may have practical applications too. "It would be a game-changing technology like the use of electromagnetism that created the modern world" says Tajmar. "Perhaps, it could open up new ways for space travel too."

But in order to come up with a way to counter gravity, we need to go beyond the theories we currently have.

"Together with my students, I'm looking into theories that predict deviations from our current understanding of gravity" he says. "We are performing experiments to test and verify those very concepts."

For an alternative theory of gravity to be taken seriously, it must be possible to reduce it to general relativity in certain scenarios. Because of this, it is necessary to test the limits of the general relativity to see where it deviates from reality and into the territory of a completely new theory.

Some of these boundaries involve strange links between gravity and other phenomena in physics, like superconductivity. In 2003, Tajmar wrote a paper proposing gravitational effects could be responsible for a difference between the measured mass of pairs of electrons at low temperatures, found in superconductors, compared to the theoretical value. This theory is known to physicists as gravitomagnetism.

"Gravitomagnetism is an approximation to Einstein's theory of general relativity for low velocities in flat space-time" says Tajmar. "It allows us to easily illustrate the effect of space-time 'frame-dragging', for example by the rotating Earth."

Frame-dragging occurs when a massive rotating object drags nearby space-time – and any objects, such as satellites, in that space-time – around with it. In the theory of gravitomagnetism, when the Earth rotates it generates a field similar to the magnetic field generated by a rotating charge. This, in turn, affects the motion of masses similar to the way electrons are deflected if they move at right angle to a magnetic field.

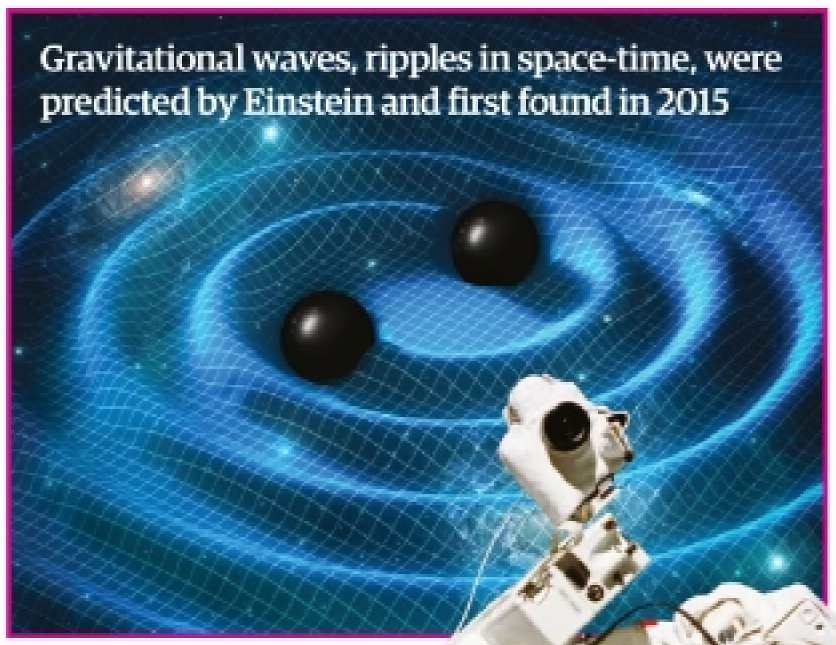
This has been measured, says Tajmar. "Satellites in polar orbit around the Earth are slightly deflected by the rotating Earth in line with Einstein's theory," says Tajmar. "However, the effect [of this frame-dragging] is so small that there are no practical applications so far." There is much more research needed before it can be used as a way to start countering gravity, it seems, or even explaining why gravity only attracts and does not repel.

Gravity is especially important when it comes to the structure of the universe. It is responsible for the formation and evolution of galaxies and black holes and, it also acts against the expansion of the universe, trying to slow it down in the face of dark energy, which is accelerating the expansion. Whether gravity or dark energy wins will decide the fate of the cosmos.

Gravitational lenses are a pretty handy tool for measuring the structure and distribution of matter in the universe. The more mass there is in a star, or a galaxy, or a cluster of galaxies, the greater the space-time distortion and the more powerful the gravitational lens. Therefore, the mass, and the distribution of that mass, can be calculated based on the amount of lensing. Yet when astronomers look at gravitational lenses formed by huge galaxy

> "Gravity is responsible for the structure of galaxies and black holes and slowing down the expansion of the universe"

The attraction of gravity holds together huge galaxies like this one, with its bright blue gas at the centre



Gravitational waves, ripples in space-time, were predicted by Einstein and first found in 2015

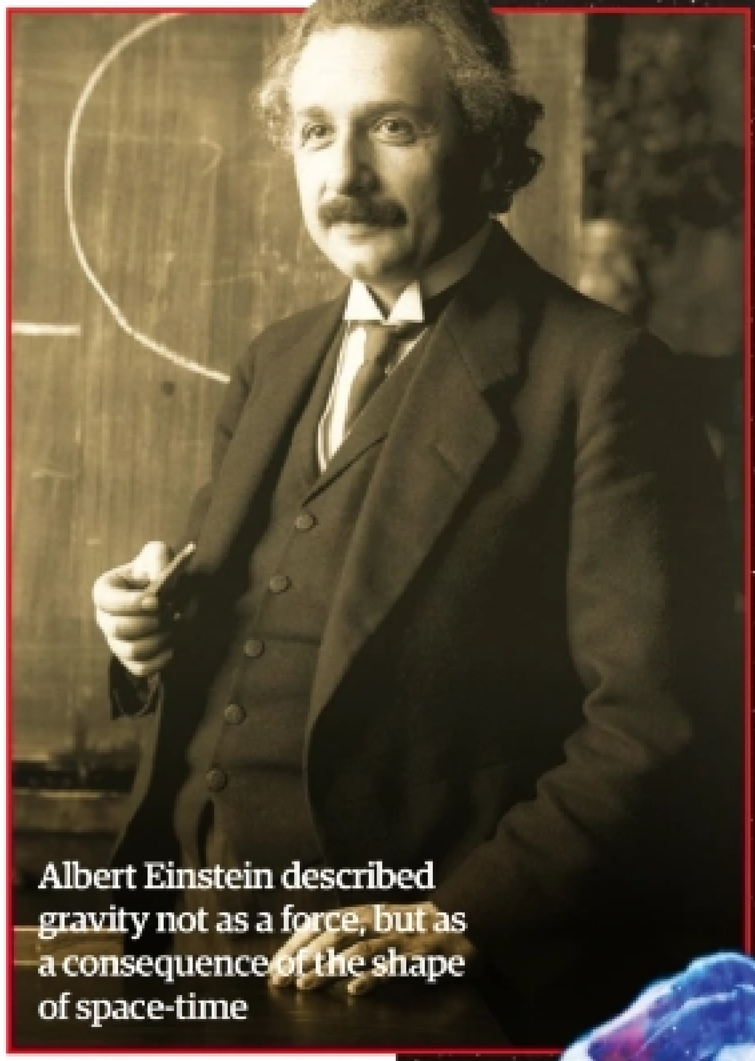
This digital collage contains a highly stylised rendition of our Solar System

clusters, the find that the lensing effect is greater than the mass of the visible galaxies can account for. The implication is that there is some unseen matter - dark matter - that is providing the extra gravity for the lenses. We also see the influence of this extra gravity in the motions of the galaxies on the outskirts of clusters, and stars on the edges of galaxies, which are moving faster than they should be based on the amount of visible matter.

What if, rather than there being dark matter to provide extra gravity, it is gravity itself, or rather our understanding of it, that is wrong? This is the theory put forward by Israeli scientist Mordehai Milgrom in 1983. He called it Modified Newtonian Dynamics, or MOND for short, and it argues that in very low acceleration environments, such as those experienced on the outskirts of galaxies and galaxy cluster, gravity does not follow the traditional theories set out by Newton and Einstein.

Practitioners of MOND are few and far between, since dark matter is by far the most popular theory, but the level of popularity doesn't necessarily dictate that a theory is correct or not. MOND has had some successes, particularly in explaining the rotation of stars around galaxies, but efforts to develop a cosmological theory of MOND, in which it co-exists in the Big Bang and Inflation theories, have so far failed. Nor does MOND have a theoretical framework from which it can be derived, leaving many scientists sceptical about MOND. However, the theory of dark matter has its own problems: nobody knows what dark matter is made of, and searches for dark matter have so far drawn a blank.

MOND does not seek to replace Newton and Einstein's theories, but to complement them, since they operate in stronger gravitational fields to MOND. At the moment, the General Theory of Relativity is our best explanation for gravity, but we know it is not the final answer. For now quantum gravity remains mysterious, but whoever can solve that puzzle which links the gravity of the very large to the gravity of the very small could change physics and our understanding of gravity forever.


Albert Einstein described gravity not as a force, but as a consequence of the shape of space-time

Five things that don't make sense about gravity

It is really weak

Although it can never reduce to zero, gravity is around 10^{40} times weaker than the electromagnetic force that holds atoms together, and no one really knows why.

We have no theory for quantum gravity

Currently, when trying to describe gravity on the tiniest scales, if we try to tie gravity into quantum mechanics, the equations just don't add up.

Gravity can only attract objects

Unlike the other forces, such as electromagnetism, gravity only works in one direction. Objects can only be attracted through gravity, not repelled.

We can't counter gravity

Because gravity is only an attractive force, we have no way of overcoming it. This is a problem for people who want to travel large distances in space.

Not everyone agrees what it really is

Some call gravity a force, but others, like Einstein, say it is not a force. Instead, it is simply a consequence of the shape of space-time.

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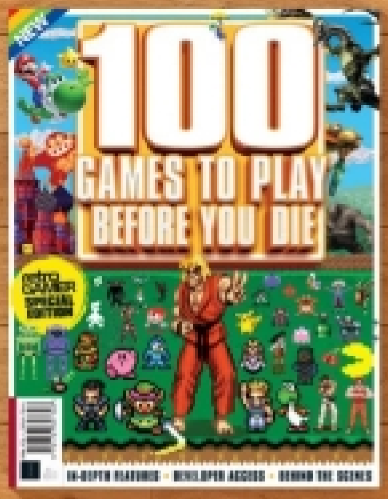

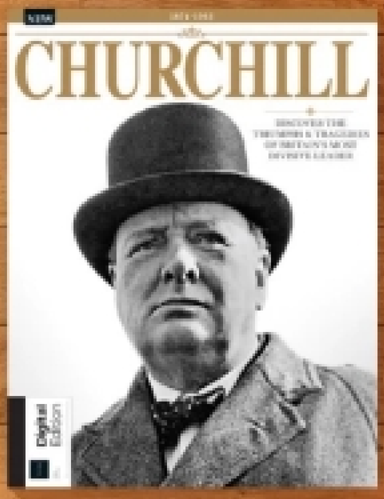
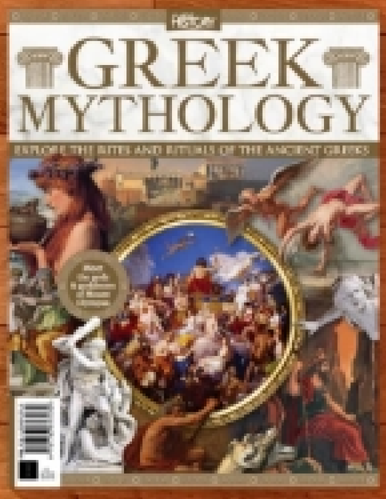
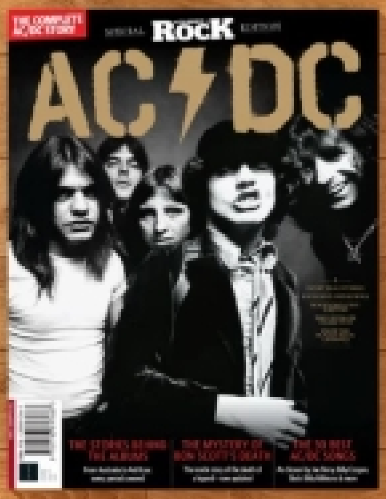
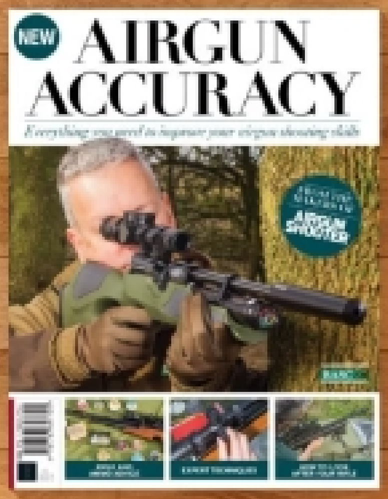

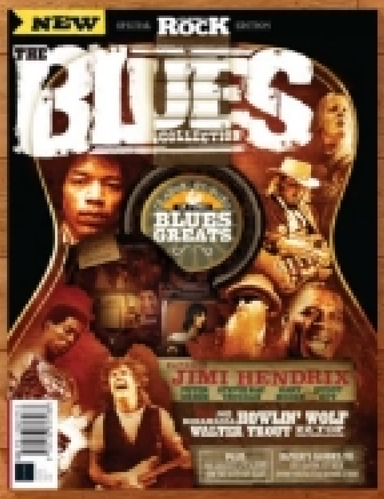
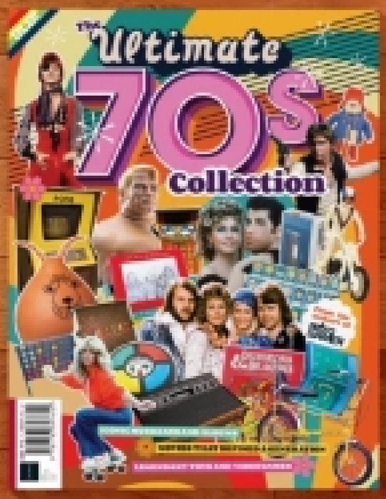

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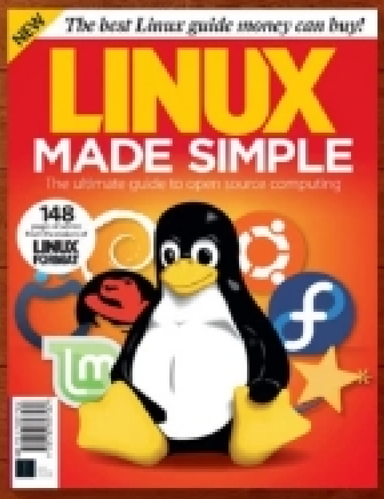
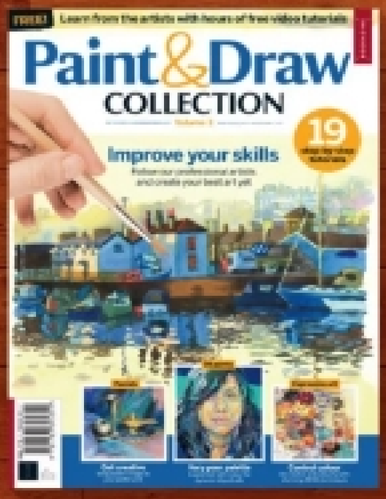

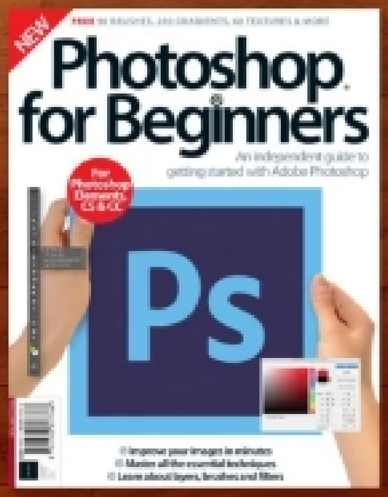
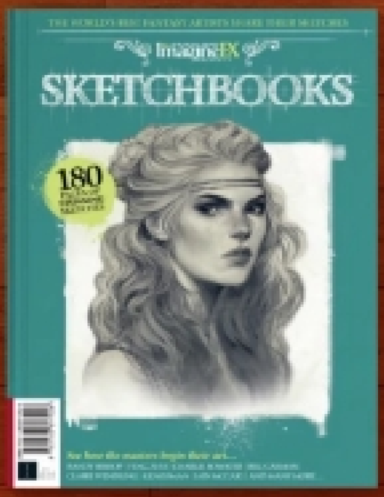
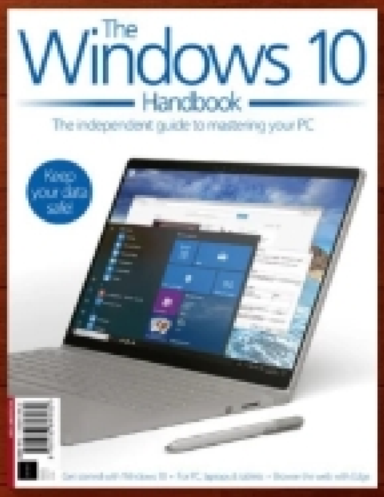
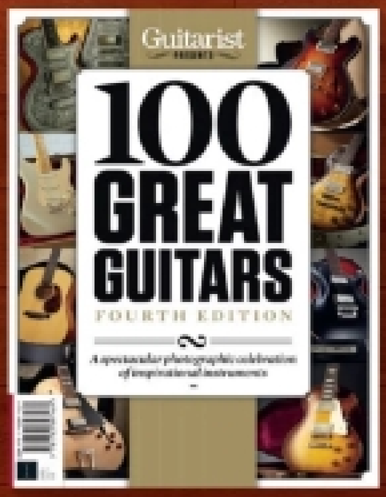

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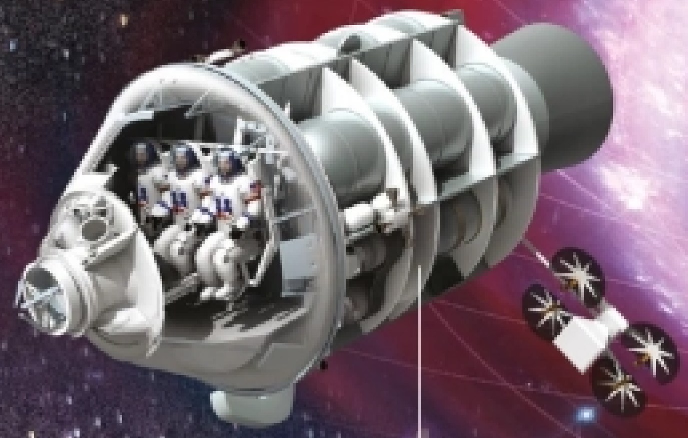

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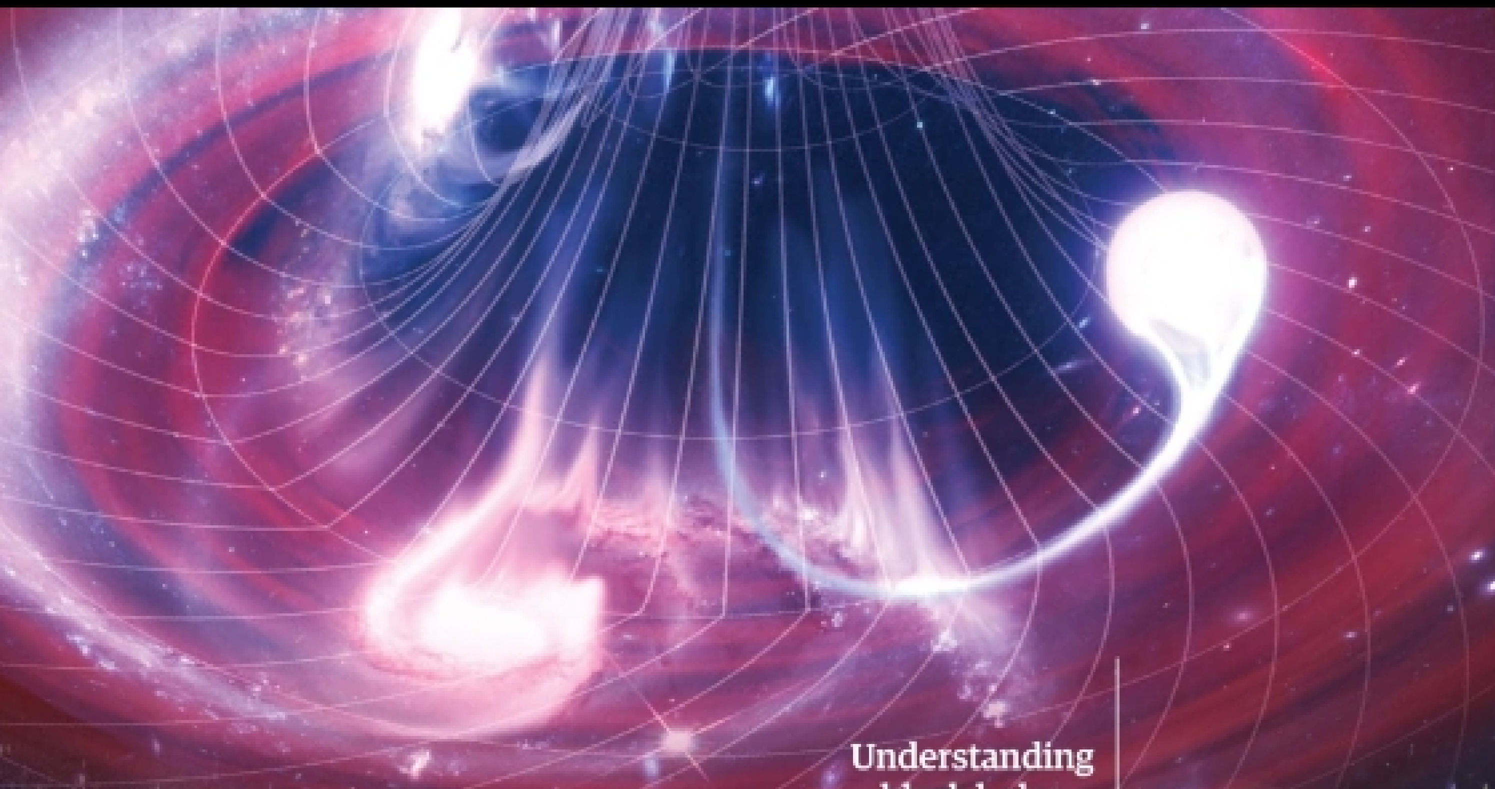

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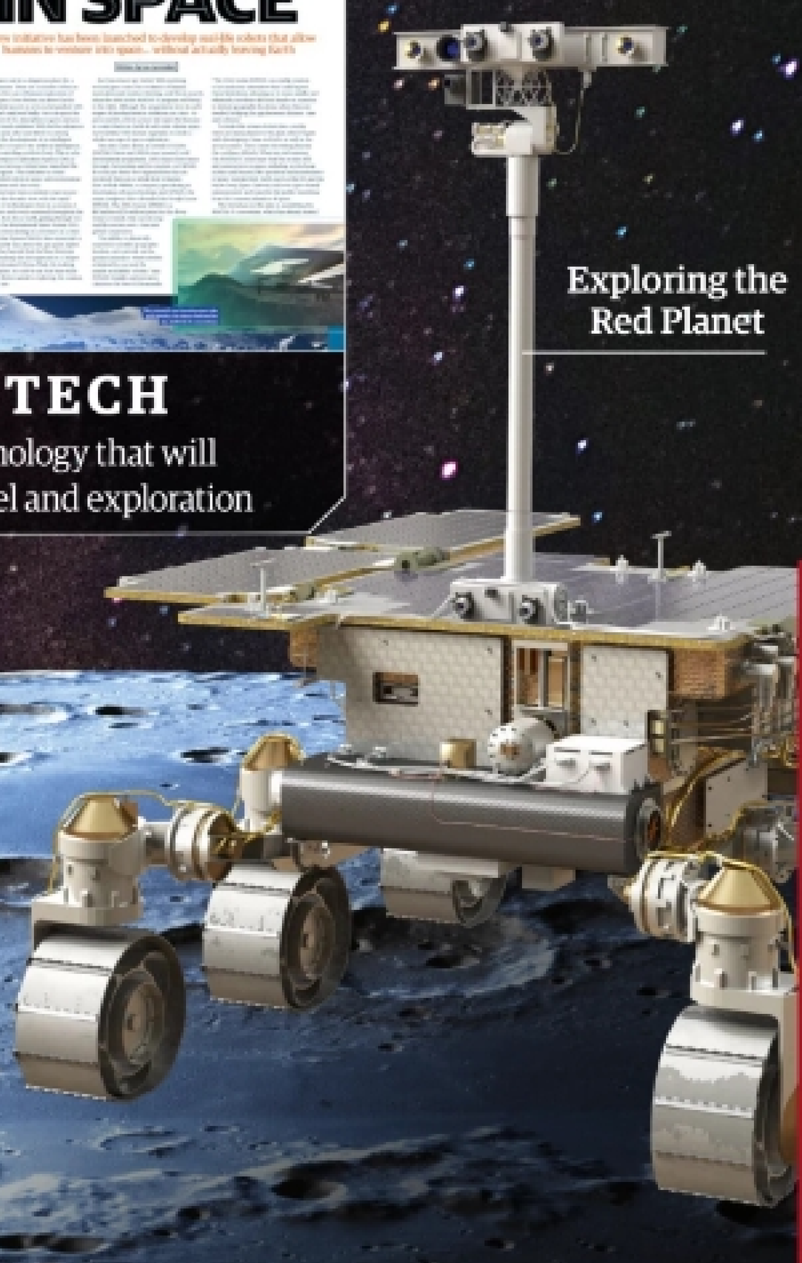

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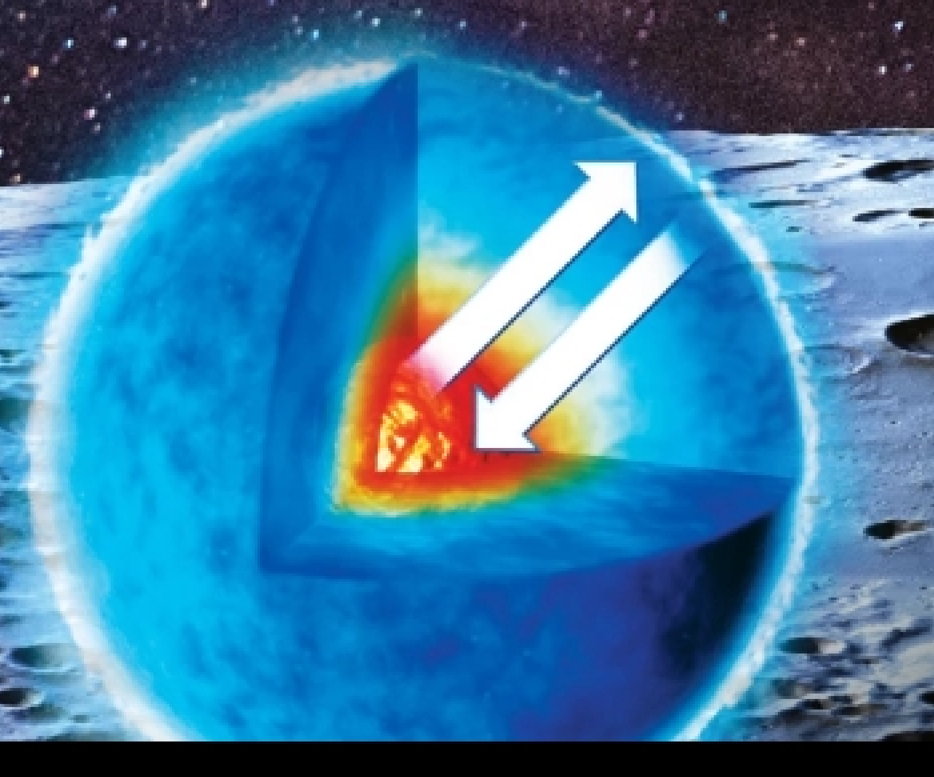

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